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COMBUSTION TOILET FOR USE ON SMALL
BOATS

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Ocean Systems, Incorporated

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COMBUSTION TOILET FOR USE ON SMALL BOATS

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Program Element 1Bb034
Contract No. 68-03-0179

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The National Environmental Research Center -- Cincinnati has reviewed this report and approved its publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Because some detail drawings have been removed, the pages of this report have been renumbered. Contact the contractor for information about the removed drawings.

FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment -- air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- o studies on the effects of environmental contaminants on man and the biosphere, and
- o a search for ways to prevent contamination and to recycle valuable resources.

Research studies on effective waste management of transportation and recreational sources have involved the development of technology for the economic treatment of wastewaters (including bilge and ballast discharges) from watercraft. Emphasis of investigations have been on treatment effectiveness, operation and maintenance requirements, safety aspects, and overall costs.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

ABSTRACT

The feasibility of providing complete treatment of human waste by means of an incinerating toilet small and inexpensive enough to be suitable for use on small pleasure boats was investigated. A toilet that avoids the need for an auxiliary power supply by relying on natural draft was built. Its performance and the quality of its effluent were evaluated.

The quality of effluent, both exhaust fumes and residual ash, is acceptable. However, the natural draft is unreliable, and the heat input needed to eliminate all odor from the exhaust fumes is greater than the unit can efficiently dissipate. The unit as constructed could potentially act as a source of ignition for explosive vapors originating elsewhere on the boat.

A redesigned unit was constructed to burn with a forced draft at a lower temperature, and to use a catalytic oxidizer to eliminate odor from the exhaust fumes. An explosive vapor detector was designed into the circuit to eliminate the possibility of igniting extraneous vapors. This unit has not been tested and evaluated.

This report was submitted in fulfillment of Project No. 15020HJK, Contract No. 68-01-0133, by Ocean Systems, Inc., under the sponsorship of the Environmental Protection Agency. Work was completed as of September 1973.

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Major Subcontractor -	LaMere Industries, Inc. Walworth, Wisconsin
WQO, EPA Project Officer -	David Cesareo
United States Coast Guard, Merchant Marine Technical Division	

SECTION I

CONCLUSIONS

1. The products of combustion of the incinerating toilet are biologically acceptable, as shown by the laboratory analysis conducted in Phase I of this study.
2. Odors of the gaseous products of combustion are not satisfactorily controlled by means of elevated temperatures alone. This is because substantial odor is generated before the elevated temperatures are attained, and because the high temperatures make it difficult and expensive to adequately disperse the flue gases, and insulate the toilet. This result caused a change in the original design intent, which was to use the combustion process as a complete, unaided treatment.
3. Odors can be reduced to tolerable levels by passing the gases through a catalytic oxidizer. The catalyst is effective at temperatures lower than those required if odor control is to be achieved solely by means of combustion.
4. The combustion toilet developed in the reported program will not perform satisfactorily without an externally-powered source of induced draft to draw combustion air into the toilet to maintain a stable flame. This is particularly the case when the flue gases must pass through the catalyst, which presents a flow restriction.
5. The toilet has been redesigned and built with an externally-powered draft and a catalytic oxidizer incorporated into it. This has been combustion-tested to verify proper operation, but has not been evaluated for efficiency and reliability.
6. It has not been demonstrated whether the toilet will aggravate an existing or potential extraneous hazard; namely, whether it will ignite explosive vapors originating elsewhere on the boat. The unit in the laboratory tests of Phase I failed its explosive environment test. Because of that, several changes were made in the design of the units built in Phase II. These changes included better sealing of the combustion chamber, improved purging, and incorporation of a vapor detector into the control circuitry. These changes have been individually bench tested, but the complete redesigned unit has not undergone an explosive environment test.

SECTION II

RECOMMENDATIONS

Based upon the results of the tests performed in Phase I of the program, several changes were made in the design of the toilet. These changes were incorporated into the construction of the two toilet units that were built during Phase II. The performance of the completed and redesigned units has not been evaluated to determine the effectiveness of the changes. The changes that were made include:

- Addition of a catalytic oxidizer to eliminate odor.
- Addition of an induced draft.
- Reduction of Btu input rate, to reduce temperature.
- Circuit redesign to add battery power.
- Circuit redesign to add a vapor detector and to reduce cost and weight.
- Improved sealing of the combustion chamber.
- Change in materials of construction to reduce weight.
- Addition of a secondary air duct around the burner.

The two units have been built for the purpose of field installation and testing. However, because of the redesign, it is recommended that some additional laboratory tests be made before any field testing is attempted.

The following specific recommendations are made:

1. Conduct an explosive environment test similar to that conducted in Phase I. This test demonstrates whether a structurally sound unit is inherently incapable of contributing to an explosive hazard. Although the addition of a fail-safe vapor detector and a programmed purge cycle is expected to have greatly reduced the practical need for explosion-proof construction, such construction still provides a tamperproof backup protection, and its function should be verified.
2. Conduct a slosh test at the severest setting that was found to be allowable in the Phase I tests. This will demonstrate whether the changes made to the combustion chamber have affected the design capability.
3. Conduct a second slosh test while attempting to maintain combustion. This will verify the effectiveness of the forced draft and the secondary air duct in improving the reliability of maintaining combustion.

4. The design package must be resubmitted to the Coast Guard for approval before installing on a boat.

5. With the necessity of providing power for a forced draft, the propane unit no longer has the intended advantage of not needing any auxiliary power source, and its remaining advantage, in comparison with the oil-fired unit, is lower initial cost. It may not be practical to continue parallel development of both units, until after one unit has been brought to the production stage.

SECTION III

INTRODUCTION

Under terms of the Water Quality Improvement Act of 1970, the Environmental Protection Agency is sponsoring the development of technology for marine sanitation devices designed to prevent the discharge of untreated or inadequately treated sewage into the navigable waters of the United States, in order to allow vessel operators to meet the requirements of proposed performance standards when they take effect. In recognition that boat and crew size in part determines the type of sanitation device that may be suitable, in the present instance particular emphasis is given to use of devices on small pleasure craft. The study reported here specifically concerns the treatment of toilet waste without galley wastes.

Ocean Systems, Inc., in conjunction with LaMere Industries, undertook to develop a combustion toilet to eliminate wastes without any discharge into the water. LaMere Industries has for several years manufactured combustion toilets for land use, in homes, and vehicles. These form a technological basis for the present design, providing experience and data on combustion characteristics of feces, and on materials suitable for the corrosive and thermal conditions that occur.

Operating conditions on a boat are rather more exacting than on land. Space and weight are at a premium and power and fuel supplies present logistics problems. Ventilation is difficult because of the watertight hull and because the compartment may be partly below water level and acts as a catch basin for liquids and heavy gases. The usual remoteness of a boat from places of refuge or assistance magnifies the seriousness of any hazard. This study has sought to adapt the combustion toilet technology to shipboard conditions.

The design approach was to use techniques of waste storage, and of heat exchange during combustion, so as to optimize the heat input required and so that the combustion period could be scheduled for the most convenient time of day and the safest weather conditions. This contrasts with the conventional operation of incinerating toilets, which burn at random intervals as they are used. The approach also included an attempt to achieve a reliable natural draft throughout the combustion cycle. If successful, this would obviate the

need for a forced-air blower, and reduce the auxiliary power requirements of the toilet. To achieve a non-polluting effluent and residue, complete combustion is necessary. A temperature of 1200°F - 1400°F, depending on the length of time at which the combustion products can be held at temperature, is needed in order to eliminate all offensive odor. This criterion established the design temperature originally chosen. The toilet was designed in both a gas-burning and an oil-burning version.

The technical design effort was augmented by a hazard analysis, an independent laboratory evaluation, and a production cost appraisal. The design package was submitted to the United States Coast Guard for review and comment on safety aspects of the toilet as installed on a boat.

In the course of the laboratory tests conducted during Phase I of this study, it has been shown that the combustion toilet provides a satisfactory treatment of wastes. However, using high temperature to control odor proved unsatisfactory, and the natural-draft unit did not maintain a reliable, stable combustion. Moreover, the absence of auxiliary power made it difficult to achieve effective purging of the combustion chamber prior to ignition, and to incorporate other control functions required or desirable for safe design. In seeking to overcome these difficulties, it was demonstrated that incorporating a catalytic oxidizer into the flue passage would provide good odor control and that inducing a draft in the exhaust flue would stabilize combustion. Further, these measures permit the use of lower combustion temperatures to achieve satisfactory waste treatment. They do require auxiliary electrical power, but this is consistent with the need for auxiliary power for control functions.

Based upon the results of the laboratory tests, the basic design approach was revised. It was concluded that a natural-draft unit is not feasible, and so the toilet combustion system was redesigned to include a forced draft and the power source necessary to drive it. With a power source available, it became feasible to make several other changes. The back pressure caused by inserting a catalytic oxidizer into the flue could be tolerated. Use of an oxidizer in turn permitted the use of lower combustion temperatures. This led to use of lighter gage materials in the combustion chamber construction, thereby reducing total toilet weight. It also lengthened burn time in order to have the same total heat input that was obtained at the higher temperatures that were initially used.

Having electrical power available made it also feasible to design a more versatile control circuit, and this was done. The circuit as now designed provides for a control sequence that includes testing for the presence of explosive vapors outside of the combustion chamber, purging of the combustion chamber, ignition, and positive fuel delivery and shutoff, and a timed burn cycle, with automatic shutdown in case of a flame-out.

A unit incorporating these features has been built to use commercial heating fuel, and another unit designed to use propane gas is partly assembled. These units are intended to be suitable for installation on boats for the purpose of gathering operating data.

SECTION IV

TOILET DESIGN

Before the basic method of waste treatment to be used was chosen, portable devices, retention systems, recirculating systems, chemical maceration systems, biological treatment systems, incineration systems, and several less conventional means of waste treatment were studied. Incineration was chosen, as being the only system offering complete treatment of wastes that would be practical to install on a small boat.

The first task to be accomplished in this project was to design and build a toilet to be suitable for marine use. This was done in accordance with EPA performance requirements that the device remove at least 90% of BOD and 90% of suspended solids from the influent, and leave a coliform density no greater than 240 per 100 ml in the effluent. The following criteria were also used:

Underwriters Laboratories, Inc., subject 1150,
"Requirements for Marine Sewage Incinerating Devices."

Safety considerations identified in the Hazard Analysis shown in Appendix A, which was prepared during the formative stages of the design.

The following description and drawings define the toilet that was designed. The present design reflects modifications that were made to comply with recommendations of the Merchant Marine Technical Division of the U. S. Coast Guard following their review of the design. Specifically, they asked for:

- A more positive prepurge of the combustion chamber, in both the propane-fired and oil-fired version.

- A more positive fuel shutoff for the oil-fired unit.

- Addition of an atmospheric bleed valve to the propane supply line (double block and bleed system).

- Elimination of the automatic re-ignition feature of the oil-fired unit.

Coast Guard comment on the original design is included as Appendix B. The modified design has not yet been submitted for review.

Design Description

The toilet is designed to incinerate both solid and liquid human waste. It is designed to be provided with its own fuel and power sources, or alternatively, to draw on the fuel and power supplies of the boat. The principal parts of the toilet are:

<u>Item</u>	<u>Drawing No.</u>
Combustion Chamber	00800066, 00800067
Burner and Burner Controls	00800099, 00400083
Flue	00400207, 00800076
Insulation	Fig. 1
Frame	00004305/306
Bowl	00400247
Flush Mechanism	00800077
Cabinet	00600128
Fuel Supply	Per Marine Engineering Regulations

The toilet is designed to draw all combustion air from outside the boat hull, and to exhaust all gases outside the hull.

The nature of the design is shown by the concept drawing SK-D-280, shown in Figure 2. The toilet is similar in size and outward appearance to a conventional water closet. Excrement is received in a bowl (labelled "hopper") beneath the seat. A "cover plate" at the bottom of the hopper can be slid aside from the aperture of the "closure" between the hopper and the "combustion chamber", allowing the excrement to fall into the chamber.

When combustion is desired, the cover plate must be slid over the aperture to seal the combustion chamber. An electromechanical interlock prevents combustion from being initiated unless the cover plate is in place, and prevents the cover plate from being slid aside while the chamber is hot. The contents of the chamber are evaporated and incinerated by heat generated by a burner (labelled "torch") located in the top central region of the chamber.

The burned gases escape from the chamber through outlet ports located at the front upper periphery of the chamber.

Fiberfrax Vari-Form B, 80 pound density-Applications which require abrasion resistance and strength, with relatively good thermal insulation, especially in the aluminum industry.

PHYSICAL PROPERTIES

As-Cast Color: Gray

Densities:

Vari-Form A 30 and 40 pounds/cubic foot.

Vari-Form B 50, 60, 70, and 80 pounds/cubic foot.

Maximum Use Temperature: 2300°F

Drying Shrinkage: Very Small

Thermal Shock Resistance: Excellent

Chemical Properties: Non-Wet by molten aluminum. Fiberfrax Vari-Form has good resistance to most chemicals with the exception of hydrofluoric, and phosphoric acids and strong alkalis.

Density, lb/cu.ft. M.O.R. (ASTM-0113-55) PSI Deformation; PSI for 5% Compression (ASTM-C165-5)	Vari-Form A		Vari-Form B			
	30	40	50	60	70	80
	20	50	130	210	300	450
	18	45	110	220	380	590
Thermal Conductivity BTU/sq.ft. in. hr., F (ASTM-C177-63)						
800°F mean	0.75	0.98	1.10	1.22	1.46	1.80
1000°F mean	0.85	1.10	1.18	1.30	1.55	1.96
1200°F mean	1.05	1.20	1.30	1.41	1.65	2.05
1400°F mean	1.20	1.28	1.38	1.50	1.76	2.10
1600°F mean	1.40	1.35	1.45	1.65	1.87	2.20

SHRINKAGE

Soaking heat for 24 hours at indicated temperature:

<u>Temperature</u>	<u>Shrinkage-%</u>
1000°F	0%
1800°F	1.6
2300°F	3.1

WATER OF HYDRATION

The binders contained in Fiberfrax Vari-Form contain water of hydration. The 11% by weight water of hydration content is completely driven off at 700°F.

FIGURE 1
INSULATION USED ON PROTOTYPE

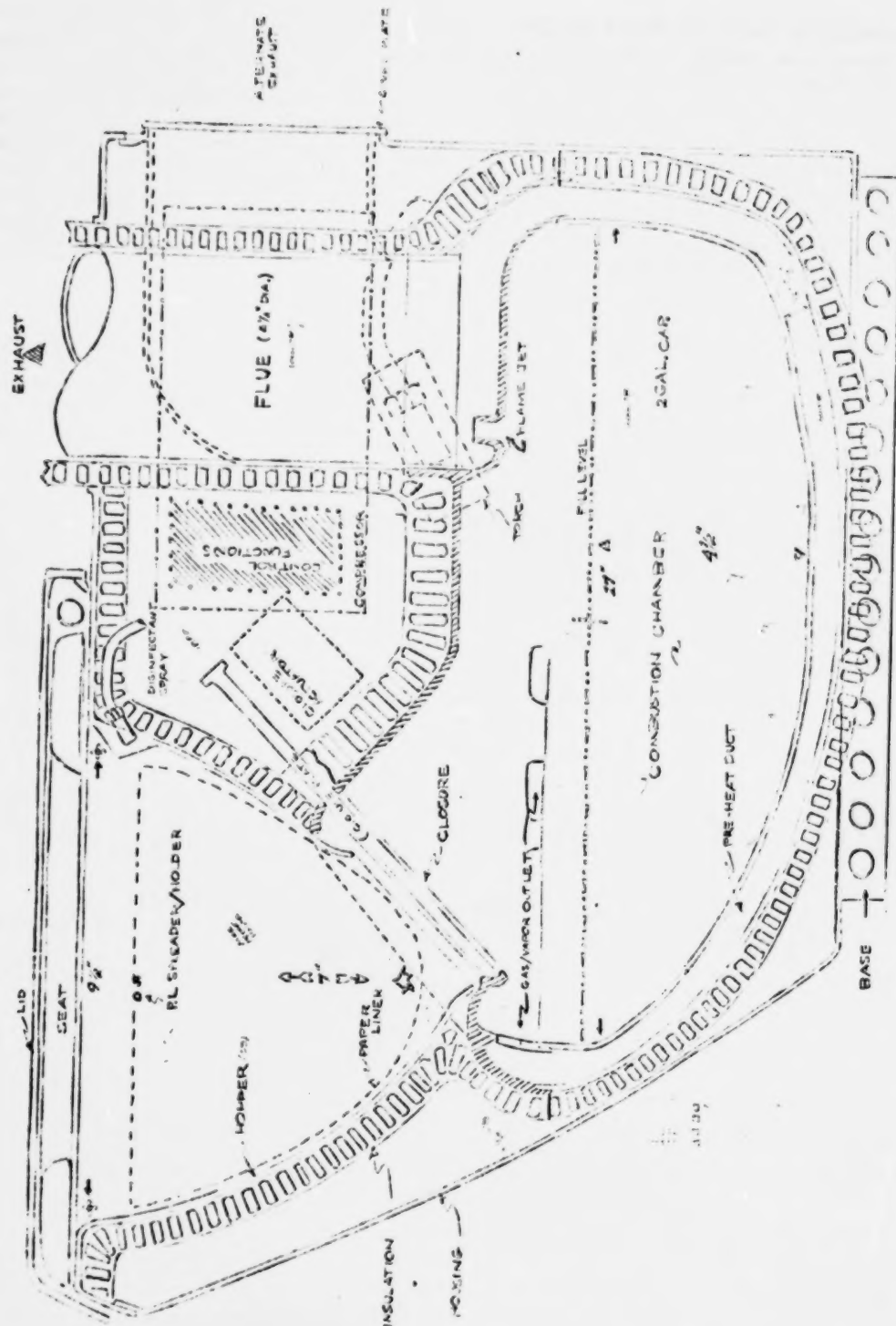


FIGURE 2. CONCEPT DRAWING SK-D-280:
INCINERATOR TOILET

They are ducted around the sides and bottom of the chamber through the space labelled "pre-heat duct". This space is created by enclosing the chamber in an insulated jacket, leaving a space about 1" wide between chamber and jacket on each side and at the bottom. Passing the gases through this space accomplishes two purposes. It allows extra time for completion of the combustion reaction before the gases are expelled, and it permits transfer of heat from the gases back into the bottom and walls of the chamber to increase the efficiency of incineration. The gases are then ducted through the flue to a point outside the boat.

Although not shown on this drawing, the flue is a double flue of concentric construction. The outer flue space is used to duct the incoming air and to preheat it. The toilet is permanently fastened to the deck of the compartment in which it is installed.

Some additional features that were originally anticipated are shown on the drawing. These are a disinfectant spray, a paper liner for the hopper, and a means (labelled "flame jet") of directing a portion of the flame directly at the exhaust gases at the base of the flame. This would be added only if it should be necessary in order to eliminate objectionable odors.

The basic toilet unit can be equipped with either of two burner and fuel systems, namely, a propane system and an oil-fired system. They operate with the assistance of 12-volt DC power that may be provided by a separate battery or may be drawn from the boat's electrical system. The oil-fired unit may have a separate gas tank or may optionally draw its fuel from the boat's fuel tank.

The assembly of major components is shown on Drawing 00800092. The nature and use of the previously mentioned components are described below:

Combustion Chamber, Drawing 00800066

Function	- To accumulate and store waste matter. - To provide an enclosure for the combustion process.
Material	- Corrosion-resistant steel, Type 316, porcelain coated.
Construction	- Formed or welded.
Capacity	- Two gallons (30 uses) when subjected to a 15°static tilt.

Cover, Combustion Chamber, Drawing 00800067

- Function - Ductile ni-resist iron
- Construction - Casting, 1/4-inch nominal wall thickness

Burner and Burner Controls, Drawing 00800099

Propane System

Function

- To provide and control a supply of heat to incinerate waste matter in the combustion chamber. Performed by a Venturi-type upshot burner rated at up to 40,000 Btu/hr.
- To provide automatic shutoff of the burner and fuel supply after a timed cycle. Performed by a mechanical-timer-operated gas valve such as an Erie Mfg. Co. valve No. 23654A.
- Other functions are common to those described on the following page for the oil burner.

Oil Burner System, Drawings 00400083, 00800099

Function

- To provide and control a supply to incinerate waste matter in the combustion chamber. Performed by the circuitry shown in the drawings, in conjunction with an air compressor/fuel induction nozzle combination.
- To provide manually-controlled ignition of the system. Performed by the spark electrodes called out as Part 8 in Drawing 00800099, energized by a 12 v. DC battery.
- To provide automatic shutoff of the burner and fuel supply after a timed cycle. Performed by the timer logic in Drawing 00800099.

- To provide automatic fuel shut-off in the event of a flame failure. Performed by the stack temperature sensor shown in Drawing 00800099.
- To prevent ignition when the combustion chamber is not sealed from the boat interior atmosphere. Performed by the lid switch in Drawing 00800099.
- To prevent ignition of explosive vapors present outside of the toilet. Performed by sensors labelled BL10 in Drawing 00800099.
- To prevent opening the combustion chamber when it is hot. Performed by a double-acting solenoid (labelled "lid open-lid closed" in Drawing 00800099) and shown also in Handle Interlock Drawing 00400300.

Flue

Function

- To effect a heat exchange between the expelled gases and the combustion and the exhaust cover shown in Drawing 00400207.
- To conduct intake air to the combustion chamber and to conduct expelled gases to the atmosphere. Performed by the transition duct shown in Drawing 00800076, and by the flue arrangement described in Appendix C.

Materials

- Components will be selected from existing manufacturers' lines. All flue components will comply with Underwriter Laboratories Standards 1150 and 103.

Insulation

Function

- To shield the functioning components, the surrounding boat structure, and the user from heat generated within the combustion chamber.

Material	- The insulation described in Figure 1.
Assembly Method	- Hand layup and heat cured.
<u>Frame</u> , Drawing 00004305/306, 00400247	
Function	- To provide support for the weight of the toilet, its contents, and its user. - To provide rigidity to insure proper alignment of functioning components. - To provide a common member to which other components may be fastened to achieve a completed assembly.
Material	- Steel, AISI-1010, ASTM A36
Construction	- Bolted
<u>Bowl</u>	
Function	- To receive discharges of human waste.
Material	- Fiberglass
Construction	- Molded
<u>Bowl Liner</u>	
Function	- To transport wastes to combustion chamber and to maintain bowl hygiene.
Material	- High density polyethylene film.
<u>Cabinet</u> , Drawing 00600128	
Function	- To provide an enclosure for the functioning components of the toilet.
Materials	- Fiberglass
Construction	- Mechanical Fasteners
<u>Fuel Supply</u>	
Function	- To provide a fuel source to sustain combustion.

Materials

- Conventional propane cylinder, installed in accordance with Marine Engineering Regulations, Subchapter F, Section 58.16-18.
- Conventional diesel fuel tank, or tap line into the boat main fuel tank installed in accordance with Marine Engineering Regulations, Subchapter F, Section 53.50-10.

FABRICATION DRAWINGS

The following pages contain the parts list, assembly drawing, and detail drawings that define the construction of the toilet units. It should be recognized that these drawings represent the toilet at a stage of development, and are not in all cases representative of the toilet as built. In particular, there have been some configuration changes in the ducting between the flue and the burner, and the final packaging of the toilet controls has not been decided, but the general scheme and function of these items are as shown on the drawings.

In the interest of saving paper and because the blue print-type drawings were not reproducible, 49 pages (containing the parts list and detail drawings) have been withdrawn. On the original report as received from the contractor, these were pages 21-69.

Description of Operation

User Operations

Defaction and Urination. The toilet is used in the same manner as a conventional water closet, with the exception that a paper liner will generally be inserted into the bowl before use. The motion to flush the toilet will be similar, although it will be a dry flush. The toilet may be used throughout the day by four to six people before an incineration cycle is necessary.

Incineration. To start the incineration cycle, the unit is operated as follows:

1. Throw the boat's main electric circuit breaker to "ON".
2. The gas detector alarm will test itself briefly, emitting a whistling sound. Wait until it stops. If it does not stop within 30 seconds, explosive gases are probably present in the boat. Do not attempt to start the toilet or the boat until all sources of leaks are detected and repaired and the boat is ventilated.
3. Make sure that the toilet flush handle is seated in the lid lock switch on the side of the unit.
4. When the alarm stops, set the timer to "FULL" or to "HALF LOAD".
5. Push the "START" switch.

Cleaning the Unit. Periodically (every several weeks depending on frequency of use), open the closure lid and vacuum or sponge out the loose ash in the combustion chamber.

Toilet Control Operating Sequence

1. The boat's main electric circuit breaker (supplied with installation kit) is switched "on". This turns on the inverters and energizes the explosive gas detectors. The gas alarm will sound for a short period, about 10 seconds, and then stop. This time will vary slightly with changes in the ambient temperature near the gas sensors. The boat engines cannot be started and the toilet cannot be ignited until the gas alarm indicates "SAFE".
2. The lid is closed, the timer is set to "FULL", or to "HALF LOAD" if the chamber is only partly full, and the toilet burn cycle is started by pushing "START" switch S-2, Drawing 00800099.

3. The burn cycle will be initiated if the explosive gas detectors BL-10-1, BL-1-2 do not give an alarm, if the lid lock switch S-4 is energized and stack temperature switch S-5 is in "low" position. The sequence of operation will be as follows in paragraphs 3.1 thru 3.3.

3.1 As an additional safety, the burner blower is turned on but the fuel is not for 30 seconds. After the toilet has been vented, the fuel solenoid and the ignition are turned on and ignition is maintained for 10 seconds and then the flame of the burning fuel maintains the burn. During this time the temperature of the catalytic reactor must rise to operating temperature or the system will be shut down.

3.2 The fuel is continuously fed to the fire chamber until the burn cycle is finished and the system timers are all reset.

3.3 After the stack temperature drops to a safe limit, switch S-5 allows the lid unlatch circuit to operate.

4. Should flame out occur at any time during the burn cycle, the stack temperature will drop and the switch S-5 will cause the timers to be reset and the lid to unlatch. The burn cycle must then be manually restarted.

SECTION V

DESIGN EVALUATION

In the first phase of this project, two combustion toilets were constructed and delivered to the Union Carbide Technical Center at Tarrytown, New York, for evaluation. One toilet was equipped to burn propane gas, the other to burn fuel oil.

The evaluation approach is described in the following test program. The laboratory report is found after the test program statement. Results and data are given in Appendix D. A commentary following Appendix D discusses the significance to the design of observation made in the course of the evaluation. A detailed procedure for the analysis of gas products is given in Appendix E.

At the conclusion of testing, the toilets were returned to the Ocean Systems, Inc., shop at Reston, Virginia, for a teardown inspection. The inspection report is given in Appendix F.

In a separate effort, a development and evaluation program on odor control was carried on at the LaMere Industries laboratory at Walworth, Wisconsin. It was demonstrated that odor could be effectively controlled by use of a catalytic odorizer. A report of this program is given in Appendix G.

Test Program for Incinerating Toilet

Objective

To evaluate the performance, suitability, and safety of an incinerating toilet intended for installation on small boats. The toilet is intended to receive and store fecal matter to a maximum amount of two gallons, representing the daily output of six persons and, upon being manually ignited, to burn the fecal matter to a sterile ash, while discharging only harmless and completely burned flue gases. It is to be capable of operating within the closed environment of a boat while being subjected to random sea motion. The test program must simulate the operating situation of the toilet.

Approach

All tests will be performed on a prototype toilet that will incorporate a combustion chamber, insulation, a burner and

control system, and a flue arrangement, all of the design tentatively planned for use on a toilet to be built for commerce.

A ship motion simulation table will be provided as a base for the toilet for those tests designed to evaluate the effect that ship motion has on performance of the toilet. The table need not be used for tests that seek only to evaluate effluent, temperature distribution, or safety hazards not related to ship motion. The design of the table is shown in Appendix H.

Test Media

Human feces will be used in the prototype toilet to collect significant data for evaluating all parameters to be tested. These are to be present in approximately the following proportions by weight: 12 part feces, 24 parts urine, 1 part toilet tissue, in a total amount of 2 gallons.

Synthetic feces may be used for setup and for trial runs. If a reliable correlation can be established, the use of synthetic feces to collect data on temperature distribution and slosh characteristics may be considered. However, all measurements of effluent and of efficiency will be made using human excrement. Synthetic excrement may be prepared according to the following receipes:

Feces: 96% canned dog food
 1% acetic acid
 3% finely granulated soap

Prepare and let stand for at least 1/2 hour before use.

Urine:	sodium sulphate (Na_2SO_4)	13.80 grams
	phosphoric acid (H_3PO_4)	4.90 grams
	calcium chloride (CaCl_2)	0.70 grams
	magnesium chloride (MgCl_2)	0.72 grams
	potassium chloride (KCI)	6.68 grams
	uric acid ($\text{C}_5\text{H}_4\text{N}_4\text{O}_3$)	1.25 grams
	urea (NH_2CONH_2)	27.00 grams
	calcium oxalate (CaC_2O_4)	0.05 grams
	sodium chloride (NaCl)	2.68 grams
	Total	57.96 grams

The above ingredients are dissolved in sufficient distilled water to make up to a volume 1,500 c.c. (1.5 liters) of solution.

Scope

Effluent Analysis

Analyze flue gases to determine concentrations, if any, of harmful or toxic substances such as coliform organisms, smoke, fly ash, objectionable odors or fumes.

Analyze ash remaining in the combustion chamber for bacteria, organic material, and mineral content.

Determine the ratio of residue ash to initial waste matter.

Operation Analysis

Measure fuel consumption and efficiency of system.

Determine temperatures at various locations in the system during the incineration cycle.

Determine how performance is influenced by ambient conditions of motion, temperature, and wind.

Verify that the unit does not introduce a fire hazard when installed on a boat.

Report

Prepare a test report containing the data, conclusions, and recommendations concerning the testing conducted in this task.

Procedures

Effluent Analysis

Solid/Liquid Effluent Analysis - Effluent analysis will be done in accordance with Environmental Protection Agency approved standard laboratory methods for Biochemical Oxygen Demands, Chemical Oxygen Demand, and Suspended Solids, and with the "Standard Methods for the Examination of Wastewater".

Because there will be no liquid effluent, it will be necessary to define and prepare a standard solution of the ash residue collected from the combustion chamber of the toilet following combustion.

Because there will be no provision for discharge of solids or liquids from the toilet into the water, the results of the analysis are to be interpreted as a potential for pollution arising from the accidental or willful discarding of residue that has been manually removed from the toilet.

Gaseous Effluent Analysis - The gaseous products of combustion, including suspended solids, and gaseous emissions which may occur during storage of feces will be measured in accordance with procedures to be identified in an amendment to this test program.

Construction and Performance Appraisal

This appraisal will follow Subject 1150 of Underwriters' Laboratories, Inc., "Requirements for Marine Sewage Incinerating Devices".

Criteria - The provisions below are excerpted from Subject 1150.

Design and Construction

Integrity - The device shall be such that no odor or noxious fumes shall escape to the boat interior when installed and operated in accordance with the manufacturer's instructions.

Flue - All devices in which combustion takes place or in which unburned fuel could accumulate shall have provision for the connection of a flue pipe terminating outside the boat. The flue shall be designed and constructed to withstand vibration, shock and corrosion and shall remain gas tight to the hull interior. The design of the flue shall be such that the combustion flame will not be extinguished nor a hazardous condition created when the outside air velocity is 40 MPH.

Operating Features

There shall be no provisions for direct or indirect overboard discharge of sewage.

The assembly shall be capable of operation without spilling any part of a normal charge of waste during a rocking action of 15° from the vertical at a rate of 3 to 4 seconds per cycle.

The incineration cycle shall be adequate to completely consume (burn to a dry ash) 120 grams of solids and 250 ml of liquids and 25 grams of ash after combustion. (N.B. For the particular unit under consideration, the above amounts should approximate 2350 gm of solids, 4700 gm of liquid, and 200 gm of paper.)

The incinerating device shall be capable of completely consuming waste products without emission of smoke, odor or fly ash to flue or into the test room. This requirement shall be deemed met when tested in accordance with USA Standard No. Z21.6-1966.

The device shall have adequate capacity to contain the ash of 20 burning cycles, with at least 10 cycles containing fecal matter, without requiring emptying to function properly.

Means shall be provided for emptying the ash from the device conveniently.

Liquid and Gas Burners - The burner and fuel supply arrangements shall be such that burner operation is not affected by roll or pitch of the boat, insofar as safety is concerned (will not twist, slide, drop out of position, or be covered while in service).

Test description, provisions and paragraph numbers are excerpted from Subject 1150.

3.1 PRE-TEST EXAMINATION

3.1.1 Production samples of the device or components to be tested, shall be operationally checked prior to testing, to determine that the device or component functions normally. Dismantling of the device or components shall be limited to that necessary to make connections and check burner settings.

3.4 SLOSH TEST

3.4.1 The device used in the previous test shall be used for this test.

3.4.2 The device shall be set up as required for the vibration test, mounted on a suitable slosh table, and an artificial charge simulating a normal usage placed in the incineration chamber.

3.4.3 The slosh table shall be adjusted to provide a rocking action of approximately 15° on either side of the vertical at a rate of 3 to 4 seconds per cycle.

3.4.4 The device shall be subjected to a total of 300 slosh cycles.

3.4.5 No hazardous condition shall be caused by this test and there shall be no evidence of failure, including spillage of the charge.

3.5 OPERATIONAL TEST

3.5.1 The device used in the previous tests shall be used for this test.

3.5.2 Operate the device in accordance with the manufacturer's instructions, and in an area free from drafts. Means for monitoring temperatures shall also be measured on internal components to determine if they are operating within their designed temperature limits.

3.5.3 The device shall then be operated continuously at its rated capacity for at least four (4) hours with external surrounding surface temperatures monitored at least hourly during this period.

3.5.4 With the device installed according to manufacturer's instructions, tests shall be performed to determine that the combustion flame will not be extinguished nor any hazardous condition develop when the outside air velocity is 40 mph from any horizontal direction.

3.5.5 The devices shall then be operated in an intermittent manner by interrupting all stages of the cycle simulating both momentary and permanent loss of the power or fuel supply and at various operating voltages.

3.5.6 The device shall then be operated and a check made of each safety appurtenance to see that it operates within the specified parameters. This shall include a check of the device under varying input voltage conditions.

3.5.7 Temperatures recorded shall not exceed those specified in Section E52-2 of this standard. No hazardous conditions shall develop and there shall be no structural failure or permanent deformation of any component as a result of any of these tests.

3.5.8 There shall be no failure or malfunction, as a result of these tests, that could cause a hazardous condition.

3.7 IGNITION TEST

3.7.1 The device used in the previous test shall be used for this test.

3.7.2 The entire device and/or individual components shall be tested according to the appropriate parts of the following procedure, depending upon the design of the device.

3.7.2.1 Assemblies so designed as to exclude vapors from the sparking source - such assemblies shall be placed in a chamber filled with a rich mixture of propane and air or gasoline and air so designed that the pressure in the chamber can be raised approximately 2 psi to simulate conditions due to atmospheric changes.

The assembly under test shall remain in the chamber for a total of eight (8) hours, while the pressure is changed gradually from one extreme to the other once every hour. Leakage shall be determined by taking vapor readings within the void being tested. Indicated vapor leakage in excess of 20 percent of the lower explosive limit will indicate that the device cannot be considered sufficiently tight to exclude flammable vapors or gases. These devices shall be subjected to Section 3.7.2.2.

3.7.2.2 Assemblies designed to prevent ignition by means other than vapor exclusion - such assemblies shall be fitted with a spark plug or other positive source of ignition located in the void occupied by the potential ignition source. In addition, a means shall be provided to purge and inject an explosive mixture of propane and air into the device. Vapor sampling to determine that the fuel-air mixture is at its maximum explosive condition may be taken within the assemblies or from the discharge. All connections shall be made through solenoid valves or other means to minimize the effect of the connections on the internal volume of the device being tested. The modified unit shall then be placed within an explosion chamber filled with the same gas mixture. Under the above conditions, the following tests shall be performed.

(a) The assembly or component shall be operated with its own potential ignition source for a minimum of one-half hour while the voltage is maintained at 110 percent of the rated voltage, one-half hour at 50 percent rated voltage and then energized at full voltage with any motor jammed. For these tests, the assembly shall have recommended overload protection.

(b) With proper flammable mixtures maintained within the assembly and in the chamber, the internal mixture shall be ignited a minimum of 25 times by means of the inserted ignition source.

(c) The above tests shall be repeated with any loose grommets or loose plugs removed.

3.7.2.3 There shall be no ignition of the flammable mixture surrounding the assembly. The results of the above procedures shall show that the assembly is sufficiently tight to exclude flammable vapors or capable of operating within an explosive atmosphere, without igniting same, or that the assembly is so constructed that, if an internal explosive mixture is ignited, it will not ignite an explosive mixture surrounding the device.

3.9 HIGH AMBIENT TEMPERATURE TEST

3.9.1 The complete device or components used in the previous tests shall be used in this test.

3.9.2 The device or components shall be placed in a heat chamber, which has an ambient temperature of $60 \pm 5^{\circ}\text{C}$ ($140 \pm 9^{\circ}\text{F}$) for a minimum of eight hours. Motor operated or other heat producing devices shall be operated in the $60 \pm 5^{\circ}\text{C}$ ambient temperature to simulate normal operating conditions.

3.9.3 There shall be no failure or malfunction that could cause a hazardous condition.

3.11 BENCH TEST

3.11.1 The tested device and components shall be disassembled and examined for compliance with all sections of this standard to determine if there are any failures not ascertained during the evaluation.

I. INTRODUCTION

Under contract to the Environmental Protection Agency, Ocean Systems, Inc., has undertaken a study of "Devices for On-Board Treatment of Wastes from Vessels." The objective of the current program has been to develop a system for the complete treatment of human wastes that is non-polluting and free of the need for shore support. The system is to be designed primarily for recreational boat use and must meet certain criteria for ease of installation, use, maintenance, reliability of performance, durability, size, cost of purchase and operation, safety and aesthetics. After careful review of six alternative treatment modes, the Engineering Division of Ocean Systems has selected incineration as the most plausible disposal method capable of meeting governmental requirements.

After design, development, and construction of two laboratory prototype combustion toilets, the Research and Development Department of Ocean Systems was tasked to conduct a short-term test program to evaluate various aspects of the toilets' performance, suitability, and safety. The scope of the program for both the liquified petroleum gas (or LP gas which is predominantly propane) and diesel oil models has included:

1. Operational Analysis
 - A. Determination of fuel consumption
 - B. Temperature measurement during incineration cycle
 - C. Effect of ambient conditions of motion
 - D. Overall performance and reliability characteristics
2. Effluent Analysis
 - A. Analytical determination of flue gas components and smoke generation
 - B. Assay of residual ash for bacteria, organic material and mineral content
3. Safety Analysis
 - A. Perform Underwriters Laboratories subject 1150 ignition test to assess potential explosion hazard.

II. EXPERIMENTAL PROCEDURE

Motion Tests

The first and perhaps most extensive phase of the testing consisted of evaluating the effects of potential sea state upon operation of the toilet. In order to simulate boat motion, a 36-inch square "motion table" was constructed (Figure 3). The table is driven by two, one-half horsepower Dayton variable speed drive motors and is capable of creating simultaneous roll and pitch amplitudes of 3°, 6°, 9°, 12°, and 15° at periods of 4.5 seconds/cycle to 1.5 seconds/cycle. The propane combustion toilet was bolted to the motion table and the inner and outer flue or stack assembly was secured to a brace for needed support during motion (guy wires were also used later as the sheet metal screws worked themselves loose from the stress). A one and one-fourth inch hole with drain plug was made in the bottom of the toilet in the outer casing to detect spillage from the combustion bowl to the outer casing during motion tests. For each test, a measured load was placed in the combustion bowl and the amplitude and period adjustments were preset. The table was turned on for about five minutes and then stopped in a rear sloping position. The drain plug was removed and any spillage into the outer casing was noted and returned to the combustion bowl. The main burner was then ignited and the table was set in motion again for a time equivalent to 300 cycles. If flame-outs occurred during this period, they were noted, burner ignition was reattempted and the test was continued for the balance of the 300 cycles. In the earlier motion tests without the splash guard, a quantity of liquid equivalent to the greatest observed spillage (2200 ml) was left in the outer casing during the burner tests.

Fuel Consumption and Temperature Measurement

Fuel consumption was determined by both weight and volume. A 20-pound (net) commercial LP gas bottle, used as the standard fuel supply, was placed on a large scale along with an American Meter Company bellows-type flowmeter with a dial readout in liters (Figure 4). For each 2.5 hour burn cycle, pre- and post-test scale and flowmeter readings were recorded and results are calculated to show total measured fuel weight, fuel weight per hour, total measured volume (converted to cubic feet) and fuel volume per hour. During testing of the diesel oil toilet, a five gallon can of Esso diesel fuel had to be suspended from a ladder in order to provide a gravity feed and fuel weight determinations were not possible. A Brooks Sho-Rate flowmeter (Figure 5), however, was used to monitor fuel flow.

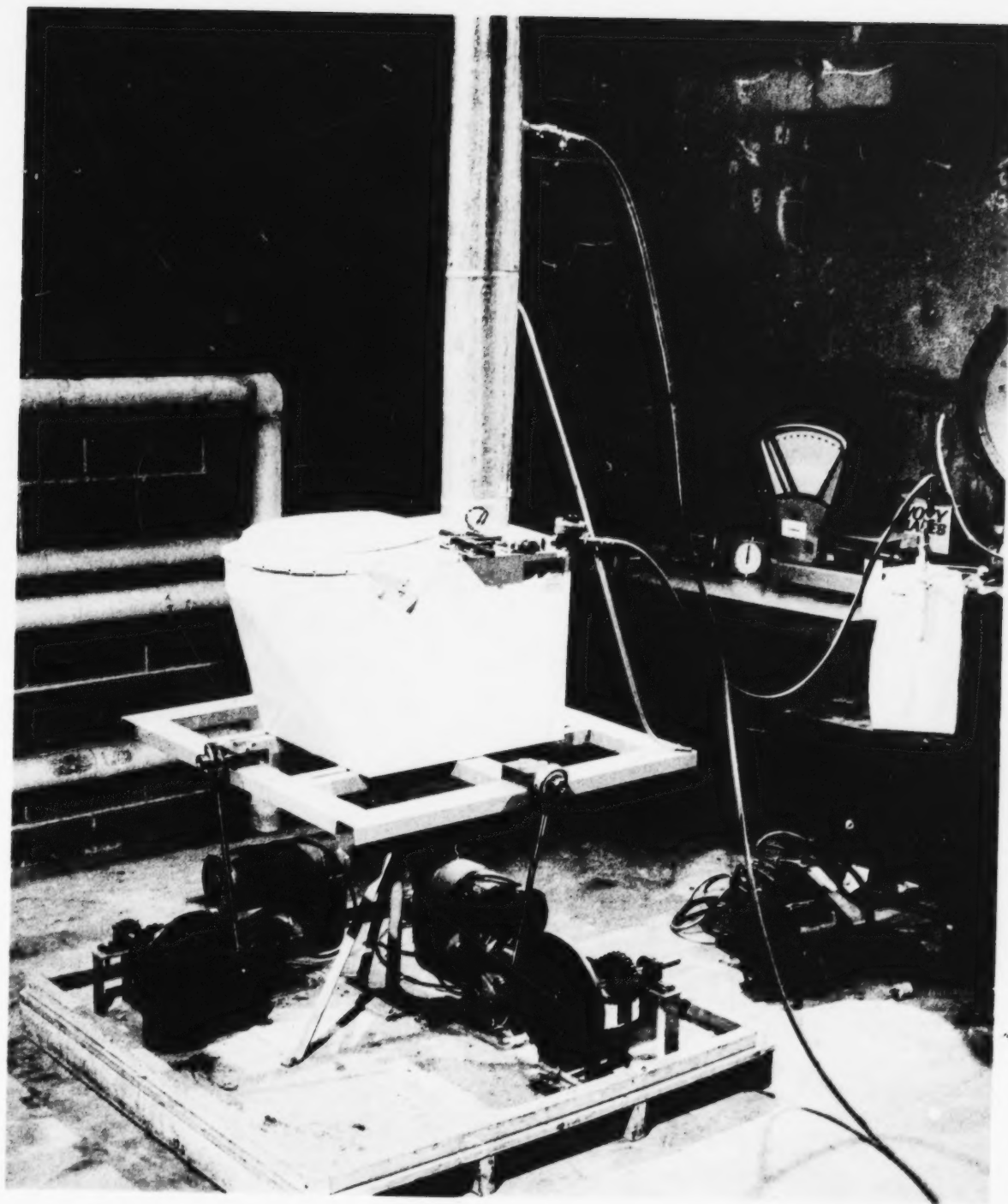


FIGURE 3. PROPANE COMBUSTION TOILET ON MOTION TABLE.

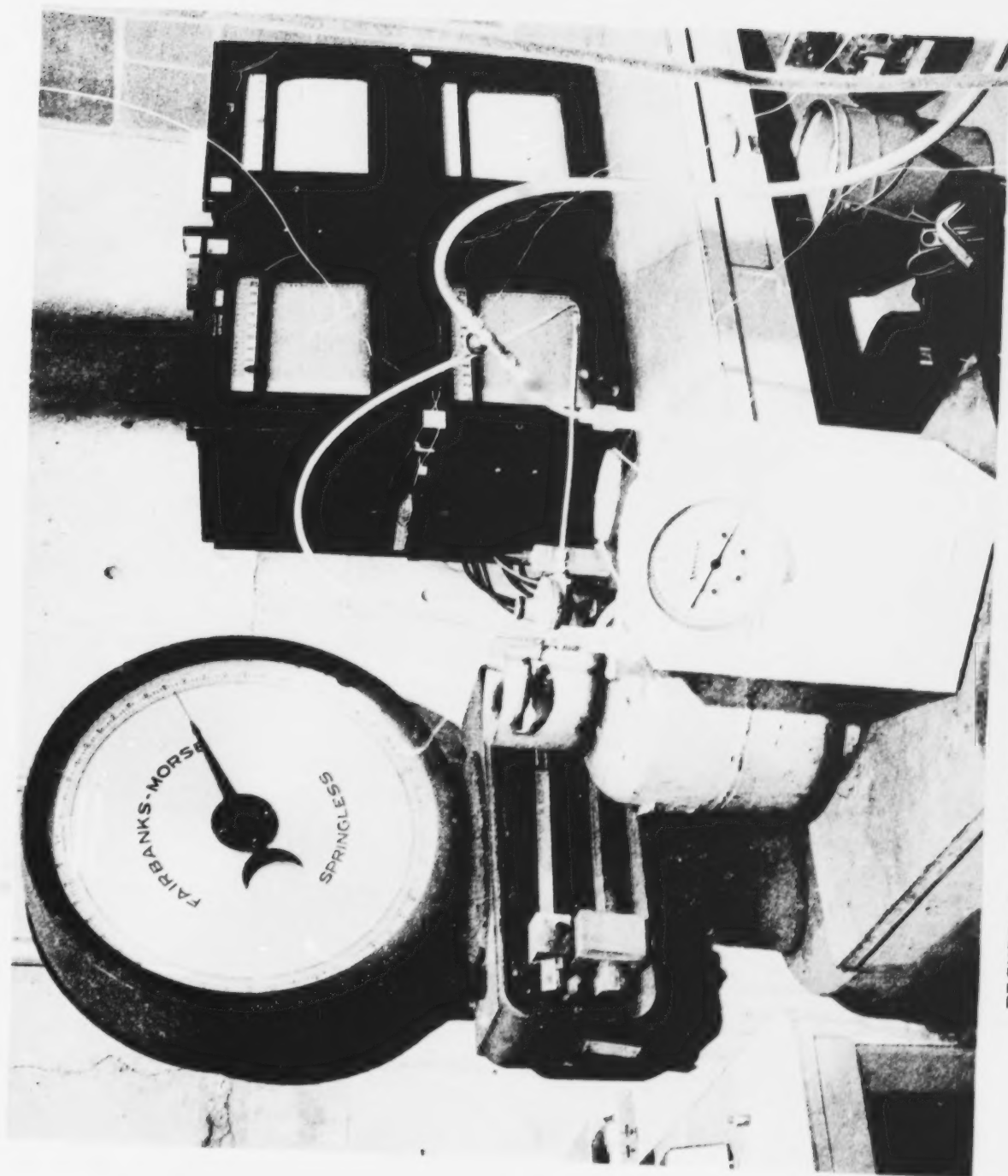


FIGURE 4. LABORATORY MEASURING EQUIPMENT: ANCILLARY APPARATUS FOR FUEL WEIGHT, FUEL FLOW AND TEMPERATURE MEASUREMENTS.

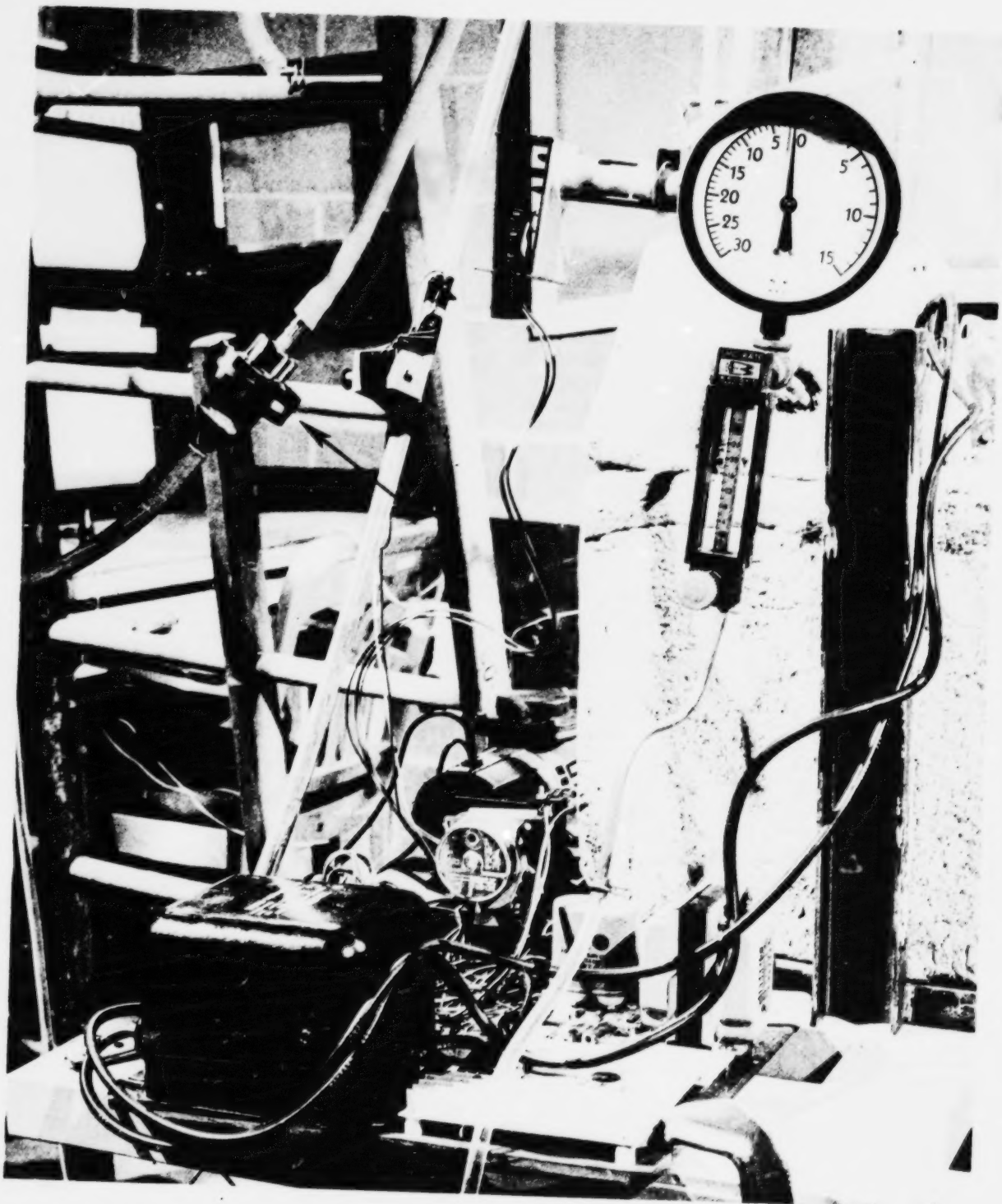


FIGURE 5: OIL COMEUSTION TOILET: DETAIL SHOWING PHASE I
BURNER CONTROLS, FUEL SYSTEM AND MILLIPORE
FILTER HOLDER FOR FLUE SAMPLING.

Temperature measurements were made with 22 gauge, type K (Chromel-Alumel) thermocouples wired to direct reading Honeywell recording potentiometers. Three recorders were calibrated in the 0 - 2000° F range and one in the 0 - 1200°C range. Temperatures were monitored at six locations at various times during the test program. These were:

1. Inside the combustion chamber both in the boiling liquid and in the flame.
2. Inside the inner exhaust flue, approximately four inches below the top.
3. At the base of the outer flue, approximately six inches above the cabinet.
4. At the front of the toilet cabinet, in the center, approximately four inches below the top.
5. At the base of the toilet cabinet directly below the above location.
6. In the center of the toilet seat opening with the cover closed.

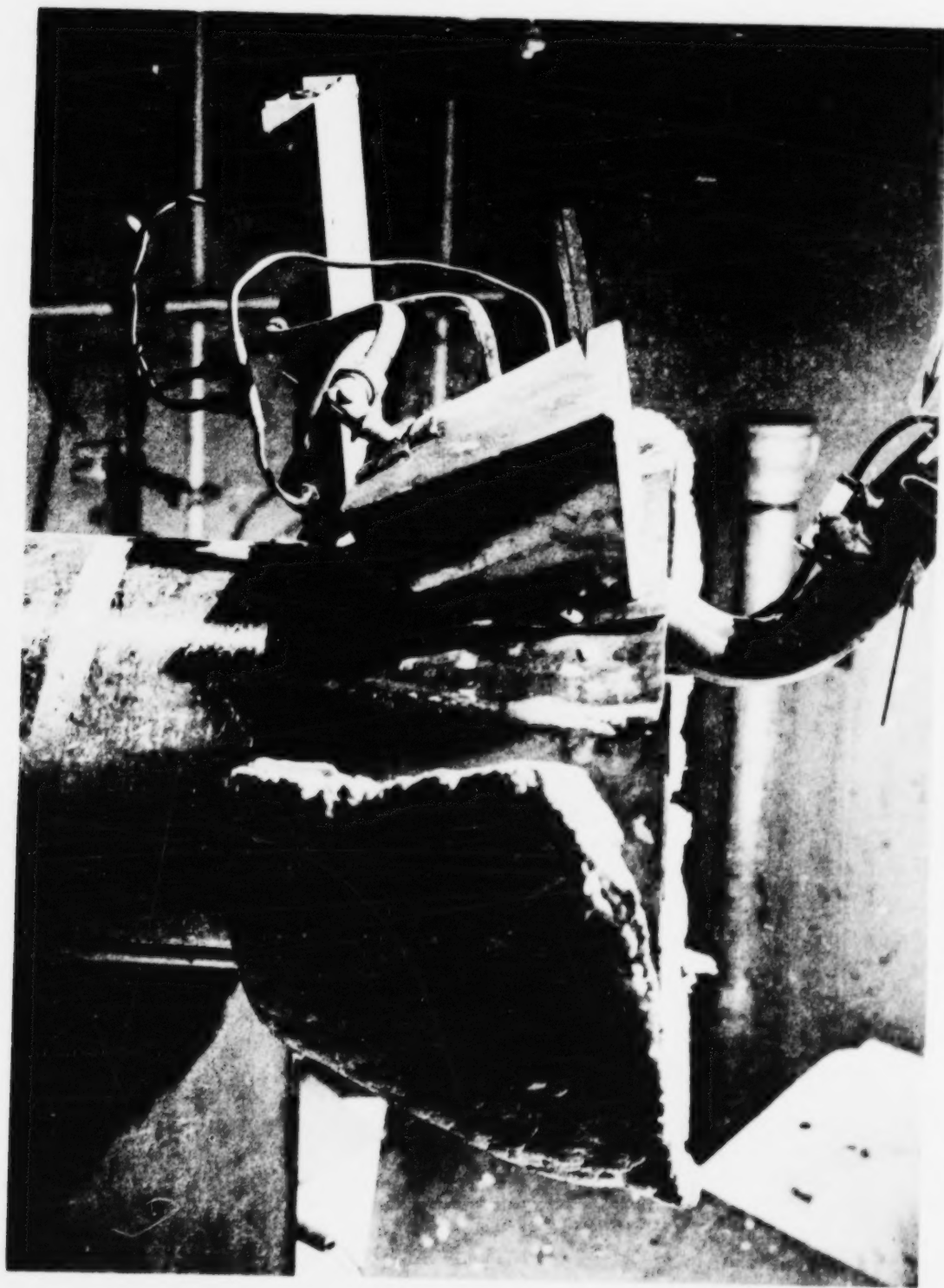


FIGURE 6. PROPANE COMBUSTION TOILET: DETAIL SHOWING
BASE OF FLUE WITH FABRICATED AIR BAFFLE TO
OUTER FLUE, MAIN AND PILOT BURNERS, THERMO-
COUPLE AND IGNITER ELECTRODE-PHASE I DESIGN

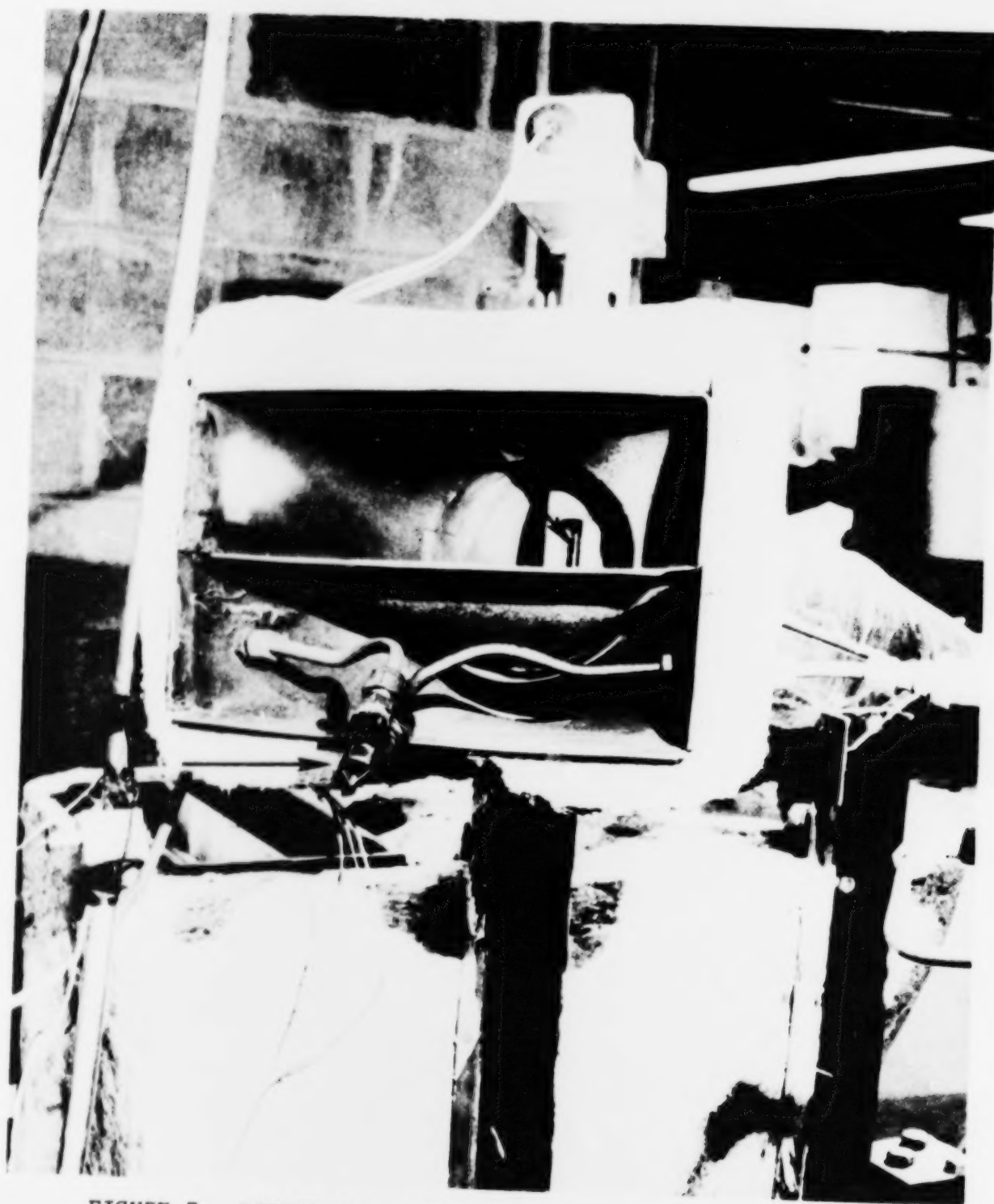


FIGURE 7. DIESEL OIL COMBUSTION TOILET: DETAIL SHOWING
OIL BURNER AND HEAT SWITCH IN LOWER EXHAUST
FLUE -- PHASE I DESIGN.

Overall Operational Characteristics

In order to evaluate the various operational characteristics of the toilets, a total of nine full cycle incineration runs were made with the propane toilet and three with the diesel oil toilet. Various combinations of real and synthetic human wastes were utilized. The synthetic materials were prepared according to the following receipes:

Feces: 96% canned dog food (Grand Union Brand)
1% acetic acid
3% finely granulated soap (Ivory Snow)

Prepare and let stand for at least one-half hour before use.

Urine: sodium sulphate (Na_2SO_4)	13.80 grams
phosphoric acid (H_3PO_4)	4.90 grams
calcium chloride (CaCl_2)	0.70 grams
magnesium chloride (MgCl_2)	0.72 grams
potassium chloride (KCl)	6.86 grams
uric acid ($\text{C}_5\text{H}_4\text{N}_4\text{O}_3$)	1.25 grams
urea (NH_2CONH_2)	27.00 grams
calcium oxalate (CaC_2O_4)	0.05 grams
sodium chloride (NaCl)	<u>2.68 grams</u>
Total	57.96 grams

The above ingredients are dissolved in sufficient distilled water to make up to a volume 1,500 cc (1.5 liters) of solution. (It was observed that neither the uric acid or calcium oxalate were completely soluble in water and these gave the synthetic urine a cloudy appearance.)

For the propane toilet, the following steps were employed for each combustion cycle:

1. Charge toilet with measured load and record.
2. Start "induction air flow" with compressed air line (Figure 8) to inner exhaust flue (this step was almost always necessary to avoid a "reversal", i.e., intake air sucked in the inner flue and through the outer casing and exhaust gas discharged through the outer flue.
3. Check inlet gas pressure (11 inches of water) open timer-operated gas valve, set gas cock safety valve to "pilot", depress and hold red thermocouple override button and

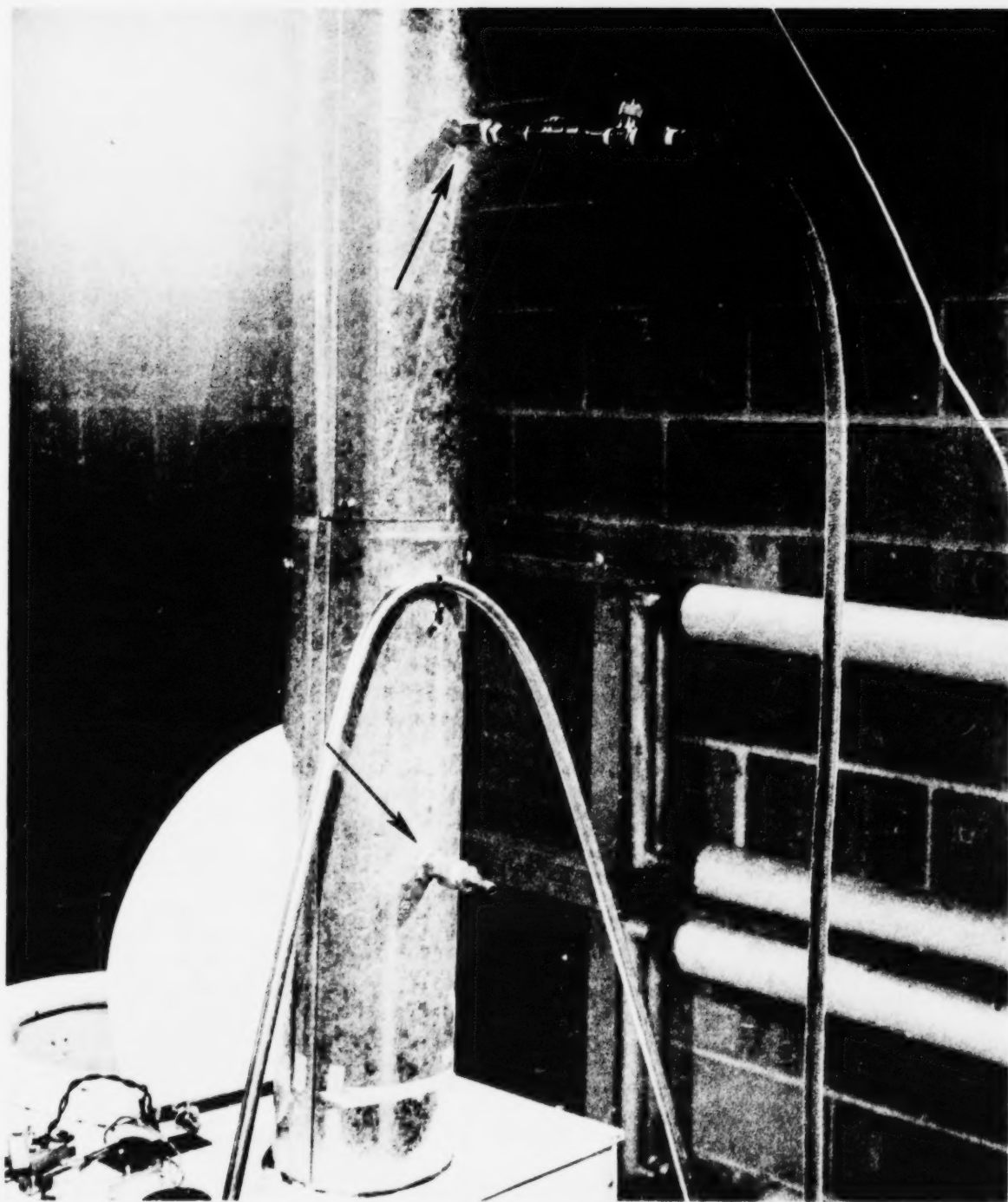


FIGURE 8. PROPANE COMBUSTION TOILET: FLUE DETAIL SHOW-
ING COMPRESSED AIR LINE INLET TO INNER FLUE
(TOP OF PICTURE) AND FLUE GAS SAMPLING
CONNECTION FROM INNER FLUE (BOTTOM OF PICTURE).

push piezoelectric igniter button repeatedly. A second person, using mirror and flashlight, observes the burner inside the toilet to note spark generation and pilot ignition.

4. After pilot ignition, valve is turned to "on" and main burner is left on for a standard cycle of 2.5 hours.

5. Observations of operation and performance are noted.

Analytical Analysis

During the course of the several combustion cycles, exhaust gas samples were taken from the inner flue into evacuated gas sampling bulbs and submitted to the Union Carbide Central Scientific Laboratory for gas chromatographic analysis. These analyses were performed utilizing Hewlett Packard 7600 Series, F & M 700, Varian 1800 and Varian 1700 gas chromatographs. The following columns and detectors were used:

1. 5A Molecular Sieve, 1/4"x6', Isothermal 60°C, Thermal Conductivity - Oxygen + Argon, Nitrogen, Carbon Monoxide
2. Carbosieve B, 3/16"x4', Isothermal 60°C, Thermal Conductivity - Carbon Dioxide
3. NC₈/Porasil C, 1/8"x12', Flame Ionization Detection, -C₁ through C₆ hydrocarbons
4. 3% OV-1, 3/16"x4', flame ionization detection, Isothermal 300°C, - Total hydrocarbons - C₁ through C₂₀ hydrocarbons
5. 5A molecular sieve, 1/4"x5', Isothermal ambient room temperature, N₂ Carrier gas, Thermal Conductivity - Hydrogen

Flue gas samples were also taken via a Millipore air-filter holder and vacuum pump. An attempt to measure gas flow with the American Standard Meter was only partially successful and volumes could not be calculated. Sampling on Run I for reflectance was over an approximate ten-minute period while sampling on Run II was done for three minutes only. Flue gas samples for coliform counts were taken in each case over a period of about three minutes.

Reflectance measurements for smoke were made using Whatman No. 3 filter paper discs. A Hunterlab Reflectometer, Model D-40 with green filter was employed. Values were calculated as percent of reflectance for clean filter discs.

The residues from both burn runs were observed to be extremely heterogeneous in color and consistency. More or less representative samples (40-50 gm) were taken for analysis. These

subsamples were powdered to a more homogeneous condition and analyzed for total carbon, loss on ignition, insolubles, coliform organisms, and thermogravimetric analysis.

Total carbon and loss on ignition were determined by standard methods in use in the Central Scientific Laboratory. Insolubles were determined by stirring a 2 gm sample with 100 ml water for 15 minutes and drying the residue on Whatman No. 40 paper at 100°C to constant weight.

Coliform counts on residue ash were determined by mixing 2 gm ash with 100 ml sterile phosphate buffer pH7.4 and filtering the soluble portion onto 0.45 Millipore filter grids followed by washing with buffer. Filters were incubated on MF Endo broth pads at 35°C and observed at 24, 48, and 72 hours. Flue gas samples were taken through 0.45 Millipore filter discs and incubated as per ash extracts.

Safety Analysis

The Marine Department of Underwriters' Laboratories has issued a Subject 1150 publication entitled "Requirements for Marine Sewage Incinerating Devices". The Research and Development Department was asked to perform the ignition test described in Section 3.7.2.2, "Assemblies designed to prevent ignition by means other than vapor exclusion". This test procedure calls for an ignition device such as a spark plug to be fitted into the combustion bowl (Figure 10) and for the whole toilet, in turn, to be placed into an explosion box which may be filled with a flammable mixture of propane and air. The explosion box prior to the test is shown in Figure 9. It should be noted that the flue is installed on the toilet in the normal manner and it protrudes through a hole in the box cover. The combustion bowl was also closed in the normal manner. A mixing fan was installed in the box and inlet connections for propane and air lines were plumbed. Two solenoid valves on a tee at the rear of the box allowed for venting and sample analysis. The sample line was connected to a Bailey Type OH100B combustible gas detector which gave "ball park" figures of the propane in air concentration. Gas samples were then taken in evacuated bulbs for exact analysis by gas chromatography. Flammability limits for propane in air range from 2% to 9% propane. At the beginning of each test, propane was bled into the box slowly until a flammable mixture was indicated on the meter. The mixing fan was left on for an additional 10 minutes while the reading stabilized. Gas samples were taken and the solenoid valves were closed. A switch on the primary line of a 15,000 volt neon sign transformer was then closed to produce a continuous spark across the plug (normal automotive gap of ~ 0.035"). The explosion box cover was sitting on a

rubber gasket but was left unbolted (Figure 9) in order to provide for pressure release. The entire apparatus was contained in a special high pressure test cubicle designed for hazardous work and the danger to personnel was minimized.

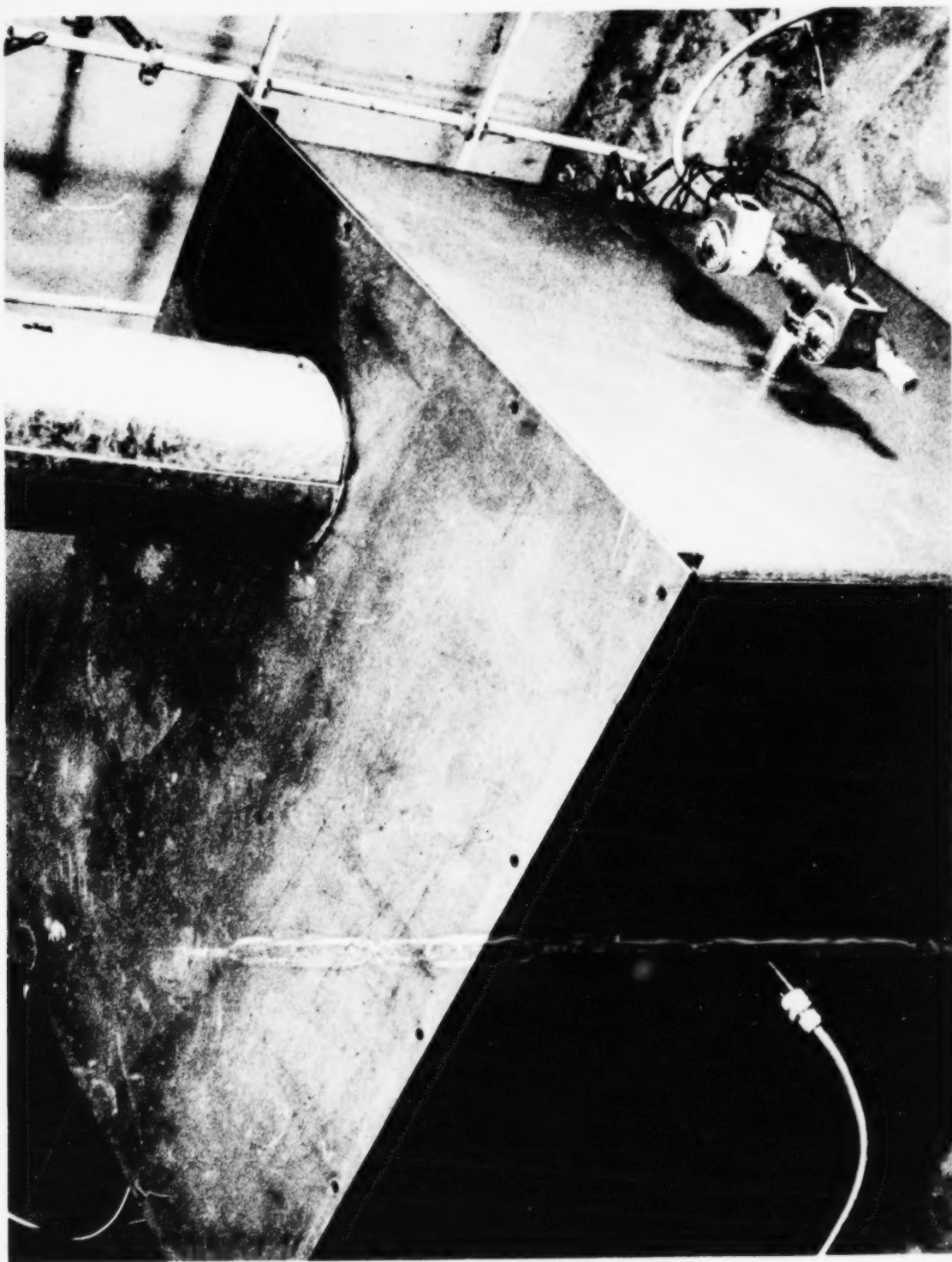


FIGURE 9. Installation of the 100-watt lamp in the 100-watt lamp fixture.



FIGURE 10. UNDERWRITERS SUBJECT 1150 IGNITION TEST; DETAIL SHOWING PLACEMENT OF IGNITION SPARK PLUG (COMBUSTION CHAMBER CLOSED PRIOR TO TEST).

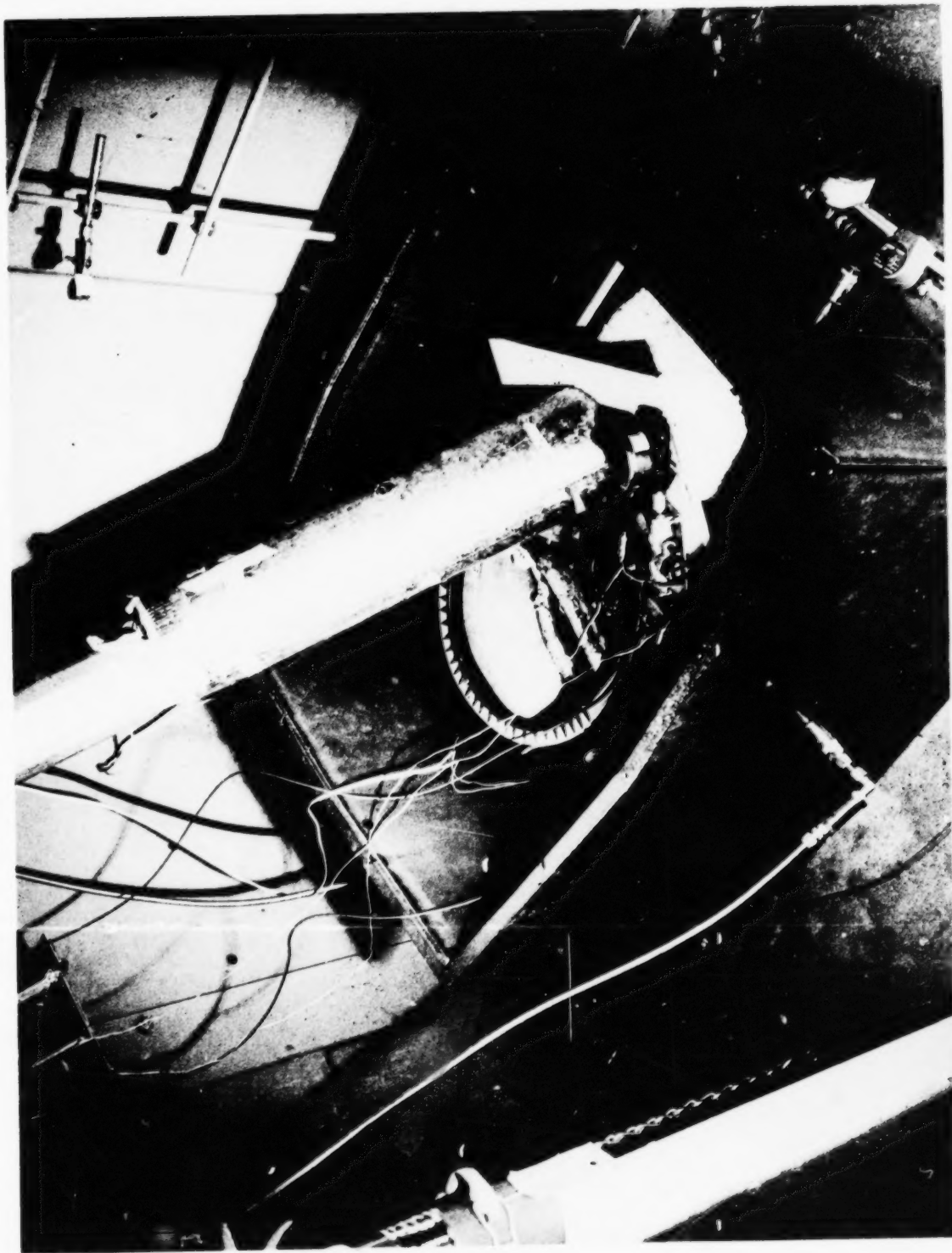


FIGURE 11. UNDERWRITERS SUBJECT 1150 IGNITION TEST:
EXPLOSION BOX SUBSEQUENT TO SECOND TEST.

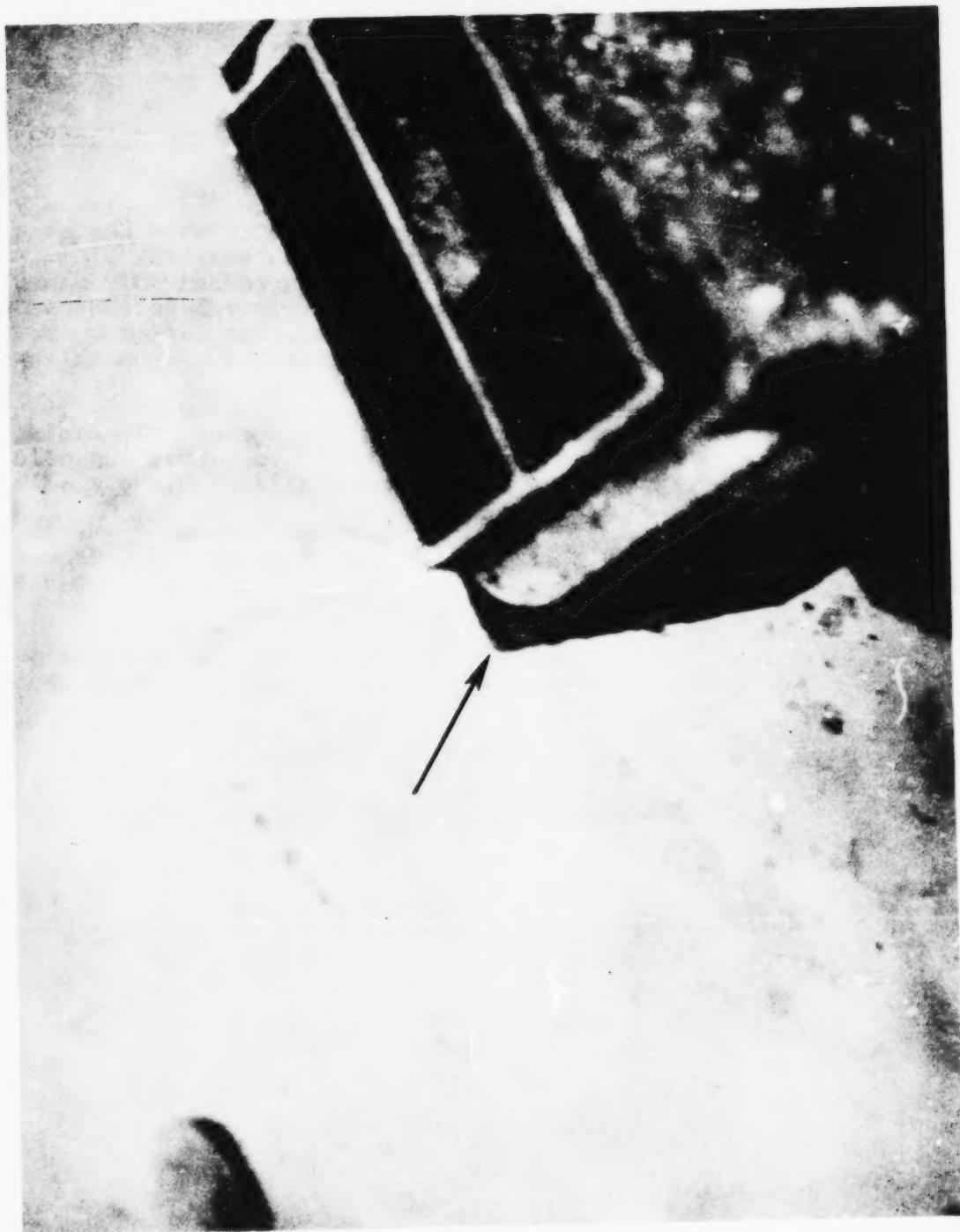


FIGURE 12. PROBABLE PATH OF GAS LEAKAGE.

SECTION VI

DISCUSSION OF PROJECT WORK

Phase I - Design and Laboratory Evaluation

The design phase of the project work is outlined in the milestone chart shown in Figure 13. *(This chart, on original report pages 100-103, has been withdrawn.)*

At the outset, studies of the feasibility of various combustion techniques were solicited from two consultants. Concepts of the toilet system and of its various components were proposed and compared. The concept shown in Figure 2 was selected as a basis for further development.

Concurrently, boat manufacturers were solicited for information that would show a correlation between boat crew size and number of heads used, and for typical head compartment dimensions. This information is summarized in TABLE 1.

Contact was made with Coast Guard personnel to identify Marine Engineering Regulations that would govern the design of the toilet.

As a basis for selection of design concepts, different techniques for combustion of liquid-solid waste mixtures were modeled in the laboratory, including the following:

- Direct impingement on surface by means of a point flame.
- Direct impingement on surface by means of a billowing flame.
- Submerged flame.
- Indirect heating by means of heating combustion chamber walls.

TABLE 1
1.1.1 - MARINE SEWAGE TREATMENT
Yacht Survey (Excerpt)

Motor Yachts - 31' to 70' l.o.a.

Boats 30' to 49' - average 1 or 2 heads

Boats 50' to 70' - average 3 heads

Typical deck area allocated for toilets -

Average 27"x27" to 36"x36"

Most heads located close to hull. In some cases, bathroom layout must be changed to simplify flue routing.

Typical Large Yacht - Huckins 65' l.o.a.

3 heads

Fwd. head - approximately 21"x24" average

Urit on raised deck - seat 27" above main deck

18" above raised deck - 38" overhead clearance

Deck to overhead - 6'3".

Yacht Crew Sizes

l.o.a.	20' - 30'	Capacity:	4-6
"	30' - 40'	"	5-6
"	40' - 60'	"	6-10

It was found that a billowing flame impinging on the surface offers the advantage of insuring that liquid vapors are heated beyond the boiling point before escaping through the flue. Indirect heating by applying heat to the chamber walls gives the most efficient heat transfer to the waste. A "double-pass" system was adopted to combine these advantages. This system uses an impinging flame, and routes the flue gases around and beneath the combustion chamber, where much of their heat is transferred back into the chamber.

Attention was then given to concepts for powering the toilet's combustion system. A U. S. Marine field stove, having a BTU output similar to that calculated for the toilet, was purchased. The stove is manually pressurized and uses fuel oil vaporized by a gas generator. It, therefore, provided a means for judging the convenience and feasibility of a manually-powered oil-burning unit. It was judged that manual ignition was incompatible with apparatus capable of isolating the burner from the boat interior atmosphere, and that the work of manual pressurization was objectionable and tended to negate the intent of designing the toilet to run unattended. Accordingly, it was decided that the oil-burning toilet would require battery power to operate the burner system. However, it was decided to seek to design a propane-burning toilet to be a self-powered unit. Since it uses fuel stored under pressure, and requires little energy to ignite, a natural-draft unit ignited by a manual sparker seemed feasible.

A fiberglass model of the proposed double-pass combustion chamber was built, and air flow characteristics were examined. Subsequently, a sheet-metal chamber was built, and preliminary combustion tests were made. These gave results approaching the design goal of two hours burn time for a six-manday accumulation of wastes. Selection of this concept was then confirmed.

Alternative propane gas control systems using manual sparkers for ignition were assembled and tested. A version using a mechanical timer-valve was selected because its limited electrical power requirements could be met by a thermally-generated current generated by the burner itself.

The basic approach was not defined: To develop a double-pass system in two alternative versions, a self-powered propane version, and a battery-powered oil-burning version. Much of the remainder of the development phase was occupied with evolving chamber and flue geometry to get best efficiency and reliable natural draft, and with developing an oil burner that would operate efficiently at the low fuel flow rate required, which is about one-half that of the smallest units

commercially available for home heating use. The general size and arrangement of the toilet adhered to the concept shown in Figure 2.

Other work included the design of toilet components, namely the flushing mechanism, the bowl, the structural members, the flue, and the cabinet work, as well as the preparation of features in the burner control apparatus. Iteration of designs was necessary, of course, as the several components are functionally interrelated. For example, the high temperature of the exhaust gases generated in the combustion chamber made it desirable to adopt a concentric flue arrangement, whereby the outer flue (for intake air) would act as an insulator for the inner (exhaust) flue. This altered the flow pattern of intake air at the flue breach, necessitating a redesign in the burner area and, of course, caused a heat exchange between intake and exhaust, which improved burner efficiency.

A review was made of Marine Engineering Regulations, and of Underwriters Laboratories Requirements for Marine Sewage Incinerating Devices. Based upon these and upon effluent test procedures made available by the Environmental Protection Agency, a test program was devised, and was submitted to the test laboratory personnel at Tarrytown for review and development of specific test procedures. As a necessary adjunct to testing, a ship motion simulator was designed and built in the Ocean Systems' workshop in Reston, Virginia. The design of the simulator is given in Appendix H.

Some work was done to develop an aerosol foam to be used as a flushing agent. The primary intent and effort has been to use a disposable bowl liner as a flushing agent. However, the efficiency of both the foam and the liner depends somewhat on the user, and will have to be established by field trials.

Construction of prototype models was carried out during December 1971 and January 1972. These units incorporated burner components, structural components, flues, and combustion chambers of the design and materials intended for production design. The cabinet work and bowl were facsimilies, however, not being critical to the parameters to be tested. The controls were in breadboard form. All functions were represented; however, the safety interlock on the flush lid was bypassed to allow ease of access for loading and observation.

The propane-fired toilet was delivered to the testing laboratory during the first week of February and evaluation of it commenced. The testing included analysis of products of

combustion, performance as affected by boat motion, efficiency, temperature profile, and safety of operation in an explosive environment. Some design modifications were made at the outset of testing, notably the addition of a slosh baffle to mitigate the effects of boat motion, and the addition of an induced draft. With these changes made, the unit was not further altered throughout the test program. The oil-burning unit was delivered for testing when tests were concluded on the propane unit.

Concurrently with the test, work was done at the LaMere Industries laboratory to find means of odor control that would be alternatives to the attempt to control odor by means of high temperatures. An arrangement of catalytic oxidizers was arrived at and delivered to the Tarrytown laboratory for inclusion in the evaluation program.

At the conclusion of the tests, the toilets were returned to Ocean Systems in Reston to undergo a teardown inspection. The results are given in Appendix F.

With the toilet delivered to the evaluation laboratory, and the design tentatively complete in its essentials, a design package was assembled that was sufficiently definitive to meet Coast Guard needs in assessing the safety of the system. The Coast Guard undertook the review, taking exception to certain features. Their report is given in Appendix B. It should be noted that the required changes do not affect the validity of test results obtained in the laboratory evaluation. These changes were incorporated into the design during the second phase of this project, in which two units intended for use in field tests were designed and built.

Phase II - Field Prototype Construction and Testing

At the outset of Phase I of this project it was planned that the functional design of the toilet would be completed in the course of Phase I and that the design effort in Phase II would be limited to such structural improvements as would be necessary for acceptable installation aboard a boat. Planned activity for Phase II included construction of two units, installation of each aboard boats, and the collection and interpretation of usage data.

However, when the results of the laboratory evaluation of the design approach that was pursued in Phase I showed that some basic redesign was necessary, it was decided to revise the scope of Phase II to include this redesign. In an effort to accomplish this within the original constraints of time and money it was agreed that the engineering hours allotted to the

gathering of data and also the duration of field testing would be curtailed and that these hours would be used to accomplish the needed redesign.

The revised plan of activity for Phase II now included functional redesign and additional laboratory evaluation to the extent needed to prove the redesign, as well as installation and the collection and interpretation of data.

The redesign included the use of new materials of construction, tighter sealing of the combustion area, addition of a catalytic oxidizer, addition of a mechanism to facilitate the use of a paper liner for the toilet bowl, and a complete redesign of the electrical circuitry to allow the addition of a forced draft, positive fuel shutoff valves, and explosive vapor detector. The additional laboratory evaluation was to include verification that the measures taken to seal the combustion system were adequate (a repetition of the explosive environment test that was conducted in Phase I), and test firing under conditions of simulated ship motion to verify that the design changes have not decreased the operational capability of the toilet.

The redesign of the electrical circuitry proved to be more difficult than was anticipated, for several reasons. First, the increased complexity made it potentially both more expensive and less reliable. To combat this, the design made extensive use of miniaturized and integrated circuitry. This was generally successful, but it was necessary in the case of some components to try the products of several manufacturers in order to obtain satisfactory reliability.

Second, an unusual shortage of electronics components at distributor outlets, and resultant long delivery times caused considerable delay in completing the design. Third, it was necessary to locate and evaluate several explosive vapor detectors before selecting one with an adequate response for this application.

Another problem that arose was the loss of availability of both boats that had been designated for installation of the toilets. Replacements for these were not found, so that it was not possible to complete the specific installation designs.

The proposed redesign was carried out and one unit, equipped to burn fuel oil, was assembled, except that the cabinet and the control component packaging is not yet in final form. A second unit, equipped to burn propane gas, is

partly assembled. A further problem is the possible unavailability of paper liners for the toilet bowl. The manufacturer who had originally shown interest in manufacturing these liners and who assisted in the design of the liner configuration subsequently gave notice that neither the configuration nor the bulk size of liner packages suit their normal production methods. They did indicate that they would assist in finding a supplier. Under these circumstances, the design of the liner release mechanism was given a low priority, and although design and construction was completed, no evaluation has been made of it.

Bench testing has been performed to verify that the unit operates properly. However, the proposed laboratory evaluations have not yet been carried out, and no installation or field testing has been done. At the present time project funds have been exhausted and work on the project has ceased.

SECTION VII

REFERENCES

1. United States Coast Guard, Marine Engineering Regulations, Subchapter F (July 1, 1970)
2. United States Coast Guard, Rules and Regulations for Small Passenger Vessels, Subchapter T (July 1, 1969)
3. Requirements for Marine Incinerating Devices, Underwriters' Laboratories, Inc., Marine Dept., Subject 1150 (March 1, 1970)
4. USA Standard for Domestic Gas-Fired Incinerators, USAS Z 21.6 - 1969, American Gas Associates, Inc. (1969)
5. Maritime Research Information Service, Treatment and Disposal of Vessel Sanitary Wastes. National Academy of Sciences (July 1971)
6. Balakrishnam, S., et al, State of the Art Review on Sludge Incineration Practice, Water Pollution Control Research Series 17070 DIV 04/70, Federal Water Quality Administration (1970)

SECTION VIII

APPENDICES

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APPENDIX A

Safety Analysis Prepared in the Formative Stage of the Design

Step #1 - Gross Hazard Analysis - This is a listing of the major hazards intrinsic to the nature of the system and its surroundings. Once having compiled the gross hazard list the next phase involves relating failures in the system that can create the subject hazard. In other words, in how many ways can a system failure cause the unsafe condition?

Step #2 - Fault Tree Analysis - This phase involves making a progressive, expanding diagram of contributing conditions. The question of "why" or "how" is asked at each step to define the steps contributing. In some situations it takes two or more conditions to result in one event, e.g., explosion requires fuel, ignition, and air. Also in certain steps the situation can be caused by two or more separate occurrences, e.g., fuel sources from engine spaces or from toilet fuel. When carried to the ultimate level this type of analysis goes down to the failure of the smallest component. When this type of evaluation is made and reliability data is available, it is possible to compute the service time involved before each event above will occur. In practice, it will be found that certain paths would occur infrequently whereas others might occur in a short time span. The latter are usually the subject of added design attention to reduce the mean time between failures and improve safety.

This type of analysis of failure can also be done qualitatively by engineering judgement as to the probability of occurrence. When all hazards have been analyzed it will be found that certain types of failures can have multiple effects, e.g., leakage past stack may contribute to several types of hazards--explosion, disease propagation, pollution, etc. Such similar failure modes are usually given additional design attention.

Once the fault tree has been prepared, a judgement (if data is unavailable) must be rendered as to the safety of the system. Usually, corrections in the design must be made. These corrections are usually directed at preclusion of catastrophic failure resulting in instantaneous death and critical failures in which death or serious harm can result if corrective action is not taken by the operator within minutes of the failure. In highly refined analyses it can also be carried to inconvenience of the operator and reduced performance considerations. Fault trees are shown in Figures 14 through 20.

Step #3 - Hazard Elimination - In this step the major hazards detected earlier are minimized or eliminated. The design procedure priority for coping with these hazards is as follows from best to poorest technique.

- 1) Design the hazard out
- 2) Install automatic safety devices
- 3) Install hazard warning systems
- 4) Establish operating procedures which minimize failure probability

Gross Hazard List

1. Explosion
 - 1.1 Ignition of explosive mixture outside of toilet
 - 1.2 Ignition of explosive mixture within toilet
 - 1.3 Explosion of fuel source
2. Fire--thermal ignition
 - 2.1 Within head compartment
 - 2.2 Exhaust from stack
3. Asphyxiation
 - 3.1 Within head compartment
 - 3.2 Proximity to exhaust flue outlet
4. Disease propagation
 - 4.1 Within head compartment
 - 4.2 Through exhaust flue
 - 4.3 Malfunction of sanitary system
5. User injury
 - 5.1 Burns
 - 5.2 Contusions
 - 5.3 Electrical shock
6.
 - 6.1 Discharge into water
 - 6.2 Discharge into air
 - 6.3 Noise
 - 6.4 Thermal discharge

Fault trees (Figures 14-20 on original pages 120-126) have been withdrawn because they cannot be reproduced.

HAZARD ELIMINATION

Explosion

The most serious hazard appears to be that of explosion, both because of the magnitude of the damage and injury that may result, and because of the suddenness and unexpectedness with which it may occur. The three elements necessary for explosion (air, fuel, ignition) are also necessary for the normal combustion process, so the hazard must be eliminated by controlling, rather than eliminating these elements.

The presence of flammable vapors from sources other than the toilet cannot be controlled by toilet design. Therefore, the toilet must be designed to isolate all sources of ignition from such vapors. A basic design approach is to draw all combustion air from outside the boat hull. (In the course of final design, an explosive vapor detector capable of de-energizing the toilet was incorporated into the control circuit to further guard against the danger of explosion.) This will preclude drawing any flammable vapors into the ignition source in the combustion chamber by way of the air intake. For the same reason, the burner should be completely enclosed within the combustion chamber or intake flue. This approach is implicit in the accompanying fault trees.

Sources of ignition external to the combustion chamber should be eliminated, so as not to be in contact with flammable vapors from extraneous sources. Potential sources may be electrical or thermal. Potential sources of electrical arcs are DC motor brushes, relays, broken wiring, and defective insulation.

A motor, if one is used, is to be remotely installed to be above the weather deck so as to be in a naturally ventilated area.

All relay and switch contacts can be designed to operate at 12 volts in an inherently safe energy range. Alternatively, they might be remotely installed, but this would necessitate lengthy leads to the electrodes, which would be subject to damage and could themselves become a source of ignition at an unsafe energy range.

All electrical insulation internal to the combustion chamber should be located in the cold air duct and behind the burner. Any electrical insulation in contact with metal parts of the combustion chamber, such as ignition electrodes, should be of porcelain. Lead wires are to be secured and supported, so as to prevent mechanical damage to the insulation.

Excessively hot surfaces as a source of ignition should be eliminated in the first instance by controlling the source of the heat. The temperature of the combustion chamber should not exceed the minimum necessary for complete combustion of feces and elimination of odor. Extending the period of time at which combustion products are held at a given temperature, and use of a catalytic oxidizer, are alternatives to elevated temperatures as means of achieving complete combustion.

A temperature-sensing stack control should be used to monitor temperature and shut down the burner if temperatures become excessive.

The combustion chamber and flue pipe are to be completely insulated so that the expelled gases form the only significant heat loss path.

These steps will eliminate external ignition sources from the design. There must also be assurance that extraneous flammable vapors are not accidentally admitted to the internal ignition source. Identifiable leakage paths are misaligned flue and combustion chamber components, inoperative seals, the combustion chamber loading breach or flushing lid, and the air intake flue.

The air intake is to extend above the weather deck or beyond the boat hull and not be in proximity to any other ventilators or fueling points.

All combustion chamber and flue breach components should be sealed with pliable, high-temperature gaskets so as to minimize the effects of misaligned components. Each gasket is to be mechanically fastened to a mating surface to preclude misalignment, or removal by the operator.

Insofar as possible, all combustion chamber, flue, and functioning components are to be mounted on a common support member so as to minimize the likelihood of misalignment.

The flushing lid must fit solidly over the loading breach of the combustion chamber. If a mechanical lock is not practical, it should be spring biased in place. It is to be equipped with an interlock to assure that it is closed whenever ignition or combustion is taking place in the chamber. Vapors can still be admitted whenever the lid is opened for a flush. The lid is to be arranged to close of its own weight, or by spring action when it is not forcibly held open, to minimize the time it will be open. Also, it is unlikely that the operator would fail to detect the scent of any flammable vapors present.

The above discussion concerns the potential of the toilet to act as an ignition source for extraneous flammable vapor. Two additional defense mechanisms can be superimposed on these. One is to assure that the toilet, if installed below the weather deck, is in a compartment that is provided with forced ventilation to prevent the accumulation of flammable gases. The second is to place the ignition controls in the same compartment with the toilet, and preferably on the toilet, so that the operator will scent the presence of any accumulation of gas.

The potential of the toilet to act as a fuel source for ignition that occurs elsewhere, and to create explosive conditions within itself must be considered. Identifiable fuel sources are: leakage from fuel tank, leakage from fuel line, excess fuel delivered to burner, and fuel delivered to burner when combustion is not taking place.

Leakage from fuel supply tanks and lines is to be prevented by adherence to applicable Marine Engineering Regulations, particularly Sections 56.50-75, 58.16, 57.50-10, 61.15-10, and 63.10 dealing with construction, installation, and testing of diesel fuel and LPG systems. Attention should be given to protecting the storage tanks from corrosive conditions and to protecting fuel lines from vibration and impact damage.

Delivery of excess fuel during combustion can be prevented by a balanced design, such that the metering device (e.g., gas orifice, induction air pressure) delivers the proper amount of fuel to mix with the air drawn through the intake and ducted to the burner. This balance is verifiable by analysis of the exhaust gases. Excess fuel delivered during combustion should not pose a significant explosion hazard, as it will be dispersed in the atmosphere outside the boat, but it should be regarded as an air pollutant.

Fuel may be injected into the combustion chamber when combustion is not taking place if the safety shutoff valve should fail. A normally-closed valve is to be used. Further assurance is obtained by situating the tank so that siphoning (in the case of an oil fuel) is not possible, if this is compatible with burner characteristics, or by using a manually operated or normally closed control valve in series with the safety valve.

Fuel is injected whenever ignition is attempted. If ignition is unsuccessful, a fuel buildup may occur. A time delay relay is to be used in combination with the heat-sensing stack control to terminate fuel injection if ignition is not achieved

within a preset time interval. The same circuitry can be designed to initiate reignition if a flameout should occur, if this should be desirable.

Identifiable causes of ignition failure are: burned electrodes, out-of-position electrodes, plugged pilot or fuel line, power failure. Burned electrodes and out-of-position electrodes are conditions that are to be prevented by rigidly positioning the electrodes outside the cone of the burner flame and in the path of the intake air so that they remain cool.

Plugged lines and burners will most likely be caused by sloshing of wastes within the chamber. This can be minimized by positioning the burner high in the chamber or in the intake duct, which is consistent with the requirements for situating electrical leads and electrodes in a cool location.

Plugged lines and power failures are fail-safe conditions insofar as explosive conditions are concerned, in that they preclude the presence of fuel.

Fuel injected into the combustion chamber will be an explosion hazard in conjunction with an outside source of ignition only if it can seep out to the ignition source. The measures previously described to prevent inward seepage will also prevent outward seepage.

Fuel injected into the combustion chamber when combustion is not taking place may cause an accumulation of flammable gas that can explode when ignition is attempted. This is prevented by inducing a draft to purge the chamber for several seconds before ignition is attempted. This is consistent with the time delay circuitry described earlier.

A minor explosion inside the combustion chamber, if it should occur in spite of the above precautions, will not be a hazard if the chamber can contain the explosion. The toilet is essentially an atmospheric system, directly vented through the flue, so pressure buildup is quickly relieved. The measures described to prevent seepage will also be effective in assuring that the flue will be the significant path of pressure relief. However, the spring mounting of the flushing lid could allow the lid to act as a poppet. To prevent this, the spring should be as strong as practical, and the lid should slide in a dovetail slot that will prevent it from moving upward to allow the escape of internal gases.

Fire

Fire is perhaps the next most serious hazard, due to the difficulty of combatting it afloat. Fire hazard would arise from combustible materials in proximity to excessively hot parts

of the toilet system. Identifiable categories of potential hot spots are: exhaust gases, exposed metal parts heated by conduction, convection, or radiation, and degradation of toilet components leading to impingement on combustibles by flame or hot gases.

Temperature of exhaust gases at the flue exit is not intended to reach the ignition temperature of cellulosic materials, such as paper, cloth, and wood. The temperature is to be controlled by minimizing the Btu input to the combustion chamber and using a temperature-sensing stack control, which is consistent with measures for elimination of explosions. Also, the flue is to be so placed, or protected, that combustible materials cannot be placed near it.

Overheating of exposed metal parts will be prevented by the same measures of insulation, ventilation, and minimization of heat input required to prevent sources of ignition for explosion.

Degradation of components specifically applies to the combustion chamber, exhaust cover, and flue, that are in direct contact with the waste matter, flame, or exhaust gases. Degradation may occur due to corrosion, oxidation, or erosion. These processes are mutually aggravating. The conditions that give rise to them, namely, the presence of corrosive wastes, heat, and motion, are inherently present in the system. Heat levels will be minimized consistent with requirements for prevention of fire and explosion. But minimizing of gas flow is not consistent with those requirements, and minimizing of waste amounts is not consistent with the purpose of the toilet. Therefore, construction materials must be chosen to withstand these conditions. The materials being used, ni-resist iron, Type 304 stainless steel, and porcelain enamel, have proved adequate in commercial applications of this nature.

Degradation may also occur to electrical insulation. This is to be prevented by locating electrical leads and components remotely, or in relatively cool locations of the toilet cabinet, and by adequate ventilation of the cabinet.

Asphyxiation

Asphyxiation is a serious hazard, as it can result in death, though its occurrence is less sudden, and easier to correct, than explosion or fire. It could occur if there were a displacement of oxygen by burned gases or carbon monoxide, either in the vicinity of the flue outlet or in the head compartment.

Carbon monoxide should not be generated in dangerous amounts, with the measures to assure complete combustion required for explosion prevention.

Gases will not be able to seep from the combustion chamber into the head compartment, with the measures taken to seal the chamber for explosion prevention.

The requirement for forced ventilation of the head compartment is a further safeguard against buildup of burned gases tending to displace oxygen.

Given the required complete combustion, gases exhausting from the flue will necessarily displace oxygen. It is necessary to disperse these gases. This will occur naturally, except under dead calm conditions when the boat is not in motion. For this condition, it is desirable that the gases be expelled by a forced draft. This would be subject to component failure, of course, although the likelihood of component failure, dead calm and zero boat motion occurring simultaneously is slight. However, as a final precaution, the flue outlet is to be so located or protected as to prevent the close approach of personnel, and is not to be located in proximity to ventilators or cabin ports.

Disease Propagation

Disease could occur if contact were made with contamination emanating through the toilet structure, through the flue, or through manual handling in the course of repairs to the unit.

Passage of bacteria or insects through the combustion chamber structure is precluded by measures taken to prevent gas seepage. Passage through the flush opening is similarly minimized by the design of the lid to remain closed except during the flush operation.

Passage through the flue is possible during storage periods when combustion is not taking place. In the case of airborne bacteria, it would be random and probably of negligible amount. Insects might be attracted by slight odors generated during storage of wastes. Their entry will be somewhat impeded if a catalytic oxidizer is interposed in the flue as a temperature-reducing measure. In any event, the hazard should be less than that associated with the average private home septic system. Experience may show the desirability of adding an antiseptic flushing ingredient.

The effectiveness of the paper liner as a flushing mechanism is not yet demonstrated in actual use conditions. If it should be inadequate, bacteria and fungus growths could be

present in the bowl and seat areas. If this is so, an antiseptic flush, or an antiseptic additive to the liner, should be considered as an alternative to periodic cleaning by the operator.

Disease borne by contaminated solids and entrained liquids in the exhaust gases will be precluded by measures to assure complete combustion. Disease associated with the decomposition of wastes should not be a problem, given the short, one-day storage period intended, but experience may show the desirability of adding an antiseptic.

Contact with waste matter when repairing the unit might be minimized either by maximizing the reliability and service life of the toilet, or by so designing it as to be easy to disassemble and clean. The latter approach would not be consistent with the requirements to minimize gas seepage and operator tampering. The former approach involves minimizing heat input, keeping burner and electrical parts in cool environments, use of heat- and corrosion-resistant materials, and sealing of the unit, which measures are consistent with requirements for prevention of fire and explosion. This approach is to be used.

User Injury

Injuries may be categorized as burns, contusions, and electrical shock.

Burns could arise from contact with hot surfaces, exposure to exhaust gases, or exposure to gases or steam escaping from an opened flush lid. Hot surfaces will be eliminated by the insulating and temperature control measures taken to prevent thermal or explosive ignition. Additionally, the toilet will be enclosed in a ventilated cabinet that is isolated from the heat source.

Exposure to flue gases will be prevented by the temperature control and installation measures required to prevent thermal ignition.

Exposure to steam and hot gases escaping from the flushing lid will be prevented by an interlock on the lid actuator that will prevent it from being opened while combustion is taking place. Additionally, the use of an induced draft in the exhaust flue would tend to cause an accidentally opened flushing lid to act as an air intake instead of an exhaust port, so that gases would not escape through it.

Contusions should be prevented by elimination of corners and sharp edges in the design and manufacture of the unit. The curved contour of the cabinet accomplishes this.

Exposed moving parts consist only of a standard toilet seat and a flushing handle that rotates in a plane parallel to the cabinet, so there should be little danger of pinching.

Electrical shock will be prevented by the low voltage and by insulating measures required for prevention of accidental ignition sources.

Pollution

Pollution may be categorized as discharge into air, discharge into water, noise, and heat discharge.

Discharge into water is not intended or possible in the operation of the toilet, except by the deliberate act of the operator in removing ash from the toilet and dumping it into the water. Complete combustion will assure that the ash is sterile and has little if any BOD potential.

Discharge of pollutants into the air will be prevented by measures that assure complete combustion, which are consistent with requirements to prevent disease propagation, asphyxiation, fire, and explosion.

Noise will be generated by the burner, and by any blower that is used in the combustion system. Some burner noise is desirable as an auditory warning measure. Blower noise objection can be mitigated in the installation by the fact that the blower is to be remotely located, for prevention of explosive ignition, and can be placed in an area where some noise can be tolerated.

Heat discharge through the flue will not be a significant input to the atmosphere, due to the relatively low thermal output of the burner. Heat discharge into the head compartment may cause discomfort. This will be mitigated by the forced ventilation required in the head compartment.

APPENDIX B



DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD

MAILING ADDRESS:
U.S. COAST GUARD (MT-2/82)
400 SEVENTH STREET SW.
WASHINGTON, D.C. 20371
PHONE: (202) 426-2160

5910/55 OCEAN SYSTEMS, INC.
5 May 1972

Ocean Systems, Inc.
Attn: Mr. T. S. McMahon
11440 Issac Newton Industrial
Square North
Reston, Virginia 22070

Gentlemen:

Subj: Your contract EPA No. 68-01-0133
Design Package for Incinerating Toilet of Small Pleasure Craft

Ref : (a) Your letter of 28 February 1972

Reference (a) stated that as a part of your contract with the Environmental Protection Agency you were to solicit an opinion from the Coast Guard regarding the safety of your incinerating toilet for use with small pleasure crafts.

The following comments apply to the control systems for both units and are offered as guidance:

a. Propane

- (1) An automatic ignition means should be provided.
- (2) A programmed pre-purge should be provided.
- (3) The valving arrangement for the burner should be an automatic double block and bleed type.
- (4) Alarm indicators should be provided.

b. Oil Unit

- (1) An automatic fuel shut-off valve should be provided.
- (2) Manual reset should be required following safety shut-down of the unit.
- (3) Alarm indicators should be provided.

Subpart 58.16 of CG-115, Marine Engineering Regulations, specifies requirements for use of liquefied petroleum gases for cooking and heating. This portion of the regulations, while not directed toward your product, could be used as guidance in designing a gas fired incinerator.

Your design package has served its purpose in assisting with this review, and is returned without action pending compliance with the above comments.

Sincerely,

A handwritten signature in cursive script, reading "C. R. Thompson".

C. R. THOMPSON
Commander, U.S. Coast Guard
Acting Chief, Merchant Marine Technical Division
By direction of the Commandant

Encl: (1) Design Package Returned

APPENDIX C

Flue Design

As of the completion of Phase I, one flue design has been used throughout and is planned to be maintained because of its inherent advantages. The design is an exhaust duct concentrically located within an intake duct.

The flue duct, at present, is a Type L venting system which has been accepted by Underwriters Laboratories, Inc. for use with an existing incinerator toilet. It is constructed with stainless steel inner pipe, galvanized steel outer pipe, and a one-fourth inch annular space between. A 4" ID, 4-1/2" OD duct has been selected.

The outer duct is a 6" ID, 6-1/2" OD Type L pipe which permits air from outside the cabin area of the boat, to enter directly into the combustion chamber. Both the intake and the exhaust duct are capped with a commercially available top.

Four features of the design stand out as advantages to the overall system:

- a. Only one opening has to be made in each deck that the flue must pass through.
- b. Intake air is preheated by the exhaust gases. The flue is actually a single pass counter flow heat exchanger.
- c. The exposed wall of the flue can be maintained within the temperature limits for human contact established by Underwriters Laboratories (105° F maximum).
- d. The combustion chamber is maintained as a closed system relative to the cabin area. Gasoline fumes or leaking propane cannot propagate into the system.

The design has one disadvantage in that its configuration is not a commercially available product. Unless a considerable market is realized, each length of annular duct will be produced at a premium. A second drawback of the design is that an axial flow blower cannot be installed in the duct because of the high exhaust temperatures. The problem is circumvented by injecting air into the exhaust section of the transition duct installed in the intake duct.

Installation

Underwriters require that a three-inch maximum distance be maintained between the exhaust duct and any combustibles. Passing the flue through a deck or ceiling requires that an opening of ten inches be cut. Standard roof flashing, screwed and sealed to the roof of the cabin, storm and trim collars and a cap complete the installation.

More operating temperature data should be compiled on the flue system described above. Heat from the combustion chamber is conducted up the outer duct wall. The transition piece, and a portion of the ducting may have to be insulated or covered to avoid being touched.

The design and application has been discussed with the manufacturer of the Type L pipe used during Phase I. He suggests that both the inner and outer wall of each duct be constructed of stainless steel. Paint, or additional corrosive protection of some type, was also recommended because of the seawater environment and elevated temperatures. Both suggestions should be investigated further.

An alternative design using a Type L inner duct and a double wall stainless steel outer duct with insulation filling (1/2" insulation) is commercially available. The insulated duct requires only two inches clearance between combustibles and ensures outer wall temperatures well within UL specifications. This design should be further evaluated.

Installation

Underwriters require that a three-inch maximum distance be maintained between the exhaust duct and any combustibles. Passing the flue through a deck or ceiling requires that an opening of ten inches be cut. Standard roof flashing, screwed and sealed to the roof of the cabin, storm and trim collars and a cap complete the installation.

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APPENDIX D

Laboratory Evaluation Results and Commentary

RESULTS AND DISCUSSION

Motion Tests

During the design and development stage of the basic combustion bowl and casing (which is the same for both burners) it was thought that sloshing caused by boat motion would be one of the major problem areas associated with the development. For this reason, the testing program was initially designed to place the greatest emphasis on operational performance and observation while under simulated sea motion. A myriad of toilet load and motion parameters were tried in the beginning before several factors became clear. The most obvious, perhaps, is that an all liquid load represents the "worst case" situation in that it is, by far, the most prone to extinguish the burner as well as spill from the combustion bowl to the outer casing through the vent hole. The addition of any solid fecal material and/or toilet paper thickened the load and made it more resistant to movement. The slosh tests were, therefore, continued using a two-gallon (7570 ml) water load in order to determine the ultimate potential for operation under motion. It is realized that the all liquid load, however, is rather unlikely to be encountered in actual practice especially if bowl liners are to be used for urination. Several solid-liquid loads were also tested for confirmation and more true-to-life simulation. When reviewing the data, one should note that the term "pitch" refers to the forward-backward motion of the toilet and that "roll" refers to the side-to-side motion. The period, in seconds per cycle, is the time the table passes through the highest and lowest points of travel and returns to the original position. Both roll and pitch motions are occurring simultaneously during the testing. It was observed that greater roll than pitch amplitudes could generally be tolerated as the forward dipping movement of the toilet served to bring the vent hole and water level closer together. For this reason, tests were usually conducted with one setting (3°) less amplitude on the pitch motor than on the roll motor.

Table 2 presents the motion tests results for the initial work. At amplitudes of 12°R (roll) and 9°P (pitch) there was no detected spillage at periods of 4, 3, and 2 sec/cycle during 300 total cycles. Heavy spillage commenced at a period of 3 sec/cycle and got progressively worse at the 2 and 1.6 sec/cycle periods. Heavy spillage began at 1.6 sec/cycle. At 15°R and 12°P, however, spillage commenced at a period of 3 sec/cycle and got progressively worse at the 2 and 1.6 sec/cycle periods. With a solid-liquid load (ratio of one part toilet paper: 20.4 parts feces: 40.8 parts urine) of the same total volume there was no spillage at the 1.6 sec/cycle setting during 300 cycles. During the burner performance evaluation, a quantity of water equivalent to the maximum recorded spillage (2200 ml) was kept in the outer casing and the burner did not ignite upon repeated attempts under any of the previous conditions. It was not determined whether or not ignition would have been achieved had the spillage been removed from the outer casing. Underwriters Laboratories (UL) Slosh Test (Subject 1150, Sec. 3.4) specifies that the marine toilet be able to perform, i.e., burn with no spillage under 15°R and P at a rate of 3 to 4 sec/cycle for 300 cycles. The propane toilet as originally tested does not meet this specification.

A splash guard, formed from a piece of V-shaped sheet metal, was subsequently fashioned and wedged into the combustion bowl, from side to side, with apex up. The guard served as an effective barrier between the vent hole and the moving water and it also prevented the water mass from moving harmonically with the toilet movement. The turbulence created also reduced the "wall climbing" ability of the load. Table 3 demonstrates the improved performance of the toilet. It now withstood 12°R and 9°P to periods of 1.7 sec/cycle. In some tests there were flame-outs before the end of 300 cycles, however, upon reignition the burner remained on for the balance of the test. One would have to repeat these tests several times in order to obtain a statically valid indication of burner performance. We do feel, all in all, that the propane toilet, as modified, would meet the UL slosh test requirements.

TABLE 2
RESULTS OF MOTION TESTS ON PROPANE TOILET
WITHOUT SPLASH GUARD

<u>Amplitude Degrees</u>		<u>Period Seconds/Cycle</u>	<u>Load</u>	<u>Spillage</u>	<u>Burner Performance</u>
<u>Roll</u>	<u>Pitch</u>				
12	9	4	Two gal. water	None	Burner did not ignite
12	9	3	"	"	"
12	9	2	"	"	"
12	9	1.6	"	Spillage begins after 2 seconds; 1425 ml water collected at end of 300 cycles	"
15	12	4	Two gal. water	None	Burner did not ignite
15	12	3	"	Spillage begins after 30 seconds; 525 ml water collected at end of 300 cycles	"
15	12	2	"	Spillage begins after 5 seconds; 400 ml water collected at end of 300 cycles	"
15	12	1.6	"	Spillage begins after 2 seconds; 2200 ml water collected at end of 300 cycles	"
15	12	1.6	4700 gm synthetic urine 2350 gm synthetic feces 115 gm toilet paper	None	No ignition attempted

TABLE 3
RESULTS OF MOTION TESTS ON PROPANE TOILET
WITH SPLASH GUARD IN PLACE

<u>Amplitude</u> <u>Degrees</u>		<u>Period</u> <u>Seconds/Cycle</u>	<u>Load</u>	<u>Spillage</u>	<u>Burner</u> <u>Performance</u>
<u>Roll</u>	<u>Pitch</u>				
12	9	4.5	Two gal. water	None	No flame out during 300 cycles
12	9	3.0	"	"	"
12	9	2.5	"	"	Burner extinguished after 49 seconds. After re-ignition, no flame out during 300 cycles.
12	9	2.0	"	"	No flame out during 300 cycles
12	9	1.7	"	Minor	"
12	9	1.7	"	Drain plug damp	"
12	9	<1.7	"	Heavy	No ignition attempted
15	12	4.4	Two gal. water	None	No flame out during 300 cycles
15	12	3.8	"	"	Burner extinguished after 49 seconds. After re-ignition, no flame out during 221 cycles.
15	12	2.9	"	"	No flame out during 300 cycles
15	12	2.5	"	"	Burner extinguished after 55 seconds. After re-ignition, no flame out during 300 cycles

TABLE 3 (Contd.)

<u>Amplitude Degrees</u>		<u>Period Seconds/Cycle</u>	<u>Load</u>	<u>Spillage</u>	<u>Burner Performance</u>
<u>Roll</u>	<u>Pitch</u>				
15	12	2.2	Two gal. water	Moderate	Burner extinguished after 53 seconds. After re-ignition, burner extinguished again after 51 sec.
15	12	2.5	6611 ml water 794 gm synthetic feces 159 gm toilet paper	None	No flame out during 300 cycles
15	12	2.2	"	"	"
15	12	1.6	"	"	"

Temperature Measurements

Temperature data are presented in Table 4. These were measured at the six locations previously described and were generally recorded at the very end of the 2.5 hour run. Temperatures inside the combustion bowls during incineration were equal to or greater than 2000°F and the bowls and residual ash glowed cherry red toward the end. The flue exhaust temperatures were significantly higher for the propane toilet measured during six runs with various loads were fairly consistent.

UL Subject 1150, Sections 2.9.12 and 2.9.13 specify that "the temperature rise of adjacent surfaces shall not exceed 67°C (120°F) . . . until the temperatures show no increase" and that "surfaces in normal body contact shall not exceed 41°C (105°F)" The terms which we have underlined are not defined and appear quite vague. Are "adjacent surfaces" part of the toilet or the floor (deck) it is mounted on or the wall (hull, bulkhead) it is next to? More important, are "surfaces in normal body contact" any outside, exposed surface which one can touch when the toilet is in operation (obviously one cannot sit on it and use it towards the end of the cycle, e.g., the temperature of the toilet seat with cover closed reached 560°F). If one makes the previous interpretation, the propane toilet, as tested, does not come close to meeting the requirement. Temperatures of the outer flue and cabinet, all exposed surfaces, significantly exceeded 105°F. It would be desirable, we feel, to seek a 140°F maximum for all exposed surfaces. This would prevent a burn if accidentally touched.

It was observed, after the first few full burns, that the plastic feet on both the toilet seat and seat cover had melted away completely (but did not catch fire, smoke or smell). They left visible stains on the toilet cabinet after the deformed masses were removed. The toilet bowl (not to be confused with the combustion bowl) began to take on a scorched and unaesthetic appearance as did the bottom of the toilet seat and toilet seat cover. The seat and cover, however, did not melt, soften or deform throughout the tests.

Fuel Consumption

Fuel usage was fairly consistent throughout the testing. These data are shown in Table 5 and can be used to estimate fuel requirements for different cycle times or fuel costs, given the unit price. On the average the propane toilet utilized 1.7 pounds

of LP gas per hour or 14.7 cubic feet per hour over the seven combustion cycles. The average 4.25 pounds measured per cycle is considerable higher than the 0.36-0.4 lbs/day estimated in the contract proposal. See commentary, Note 3.

General Performance and Reliability Characteristics

The laboratory testing personnel encountered a variety of problems and difficulties associated with the general design, performance, operation and reliability of both the propane and diesel oil toilets. Many of these may be those normally associated with the testing of the first prototype of any complex new design and they may be easily resolved with some additional time and effort. Some, indeed, are quite minor and may just be associated with the breadboard construction. They did all add up, however, to make both units, as we received them for testing, impractical and not recommended for marine evaluation without additional improvements. To assist the engineers in the redesign, we have summarized the various findings in tabular form and have suggested some "food-for-thought" solution ideas where possible (the table is not ranked according to importance). See commentary, Note 4.

TABLE 4
TEMPERATURE MEASUREMENTS DURING COMBUSTION

Toilet	Load	Time of Measurement, Hrs.	Inside Combustion Chamber	Inner Exhaust Flue, 4 inches From Top	Temperature °F	
					Base of Outer Flue	Front of Toilet Cabinet At Top Center
Propane	6610 ml synthetic urine	2.0		870	370	175
	794 gm synthetic feces					
Propane	4000 ml real urine	2.5		820	220	158
	3576 ml synthetic urine					
Propane	6610 ml synthetic urine	2.5		870	340	194
	794 gm synthetic feces					
	159 gm toilet paper					
Propane	6610 ml synthetic urine	2.5		900	290	158
	794 gm synthetic feces					
	159 gm toilet paper					
Propane	5 actual usages of urination and defecation	2.5		870	250	
	1 defecation only					
	1 urination only					
Diesel Oil	3000 ml real urine					
	5 real defactions	1.5	2000	420	220	
Oil	4300 ml real urine					

TABLE 4 (Contd.)

<u>Toilet</u>	<u>Load</u>	<u>Time of Measurement Hrs.</u>	<u>Inside Combustion Chamber</u>	<u>Base of Toilet Cabinet at Bottom Center</u>	<u>Center of Toilet Seat Opening With Cover Closed</u>
Propane	5425 ml synthetic urine	2.5	2000	130	560
	2166 ml real urine				
	794 gm synthetic feces				
	159 gm toilet paper				

TABLE 5

Load	Total Burning Time, Hrs.	Total Measured Weight, lbs.	Pounds/ Hr.	Total Measured Volume, cu.ft.	Cubic Ft/ Hr.
6610 ml water	2.5	3.88	1.55	35.6	14.2
794 gm synthetic feces					
159 gm toilet paper					
6610 ml synthetic urine	2.0	4.25	2.13	34.6	17.3
794 gm synthetic feces					
159 gm toilet paper					
4000 ml real urine	2.5	4.25	1.70	36.6	14.6
3576 ml synthetic urine					
6610 ml synthetic urine	2.5	4.25	1.70	36.1	14.4
794 gm synthetic feces					
159 gm toilet paper					
7570 ml synthetic urine	2.5	3.25	1.30	32.5	13.0
6610 ml synthetic urine	2.5	4.50	1.80	37.3	14.9
794 gm synthetic feces					
159 gm toilet paper					
5429 ml synthetic urine	2.5	4.25	1.70	35.8	14.3
2166 ml real urine					
794 gm synthetic feces					
159 gm toilet paper					

Note: Fuel weight accuracy - ± 0.25 lbs.

Propane Toilet

<u>Problem Area</u>	<u>Problem</u>	<u>Possible Solution(s)</u>
Ignition System	1. Plastic insulation on igniter wire melted off in short order. 2. Igniter wire fell off electrode contact. 3. Piezoelectric system produced intermittent sparks and was generally unreliable. Possible causes: (a) Electrode moved out of position frequently due to heat sag. (b) Electrode resistance increased due to surface dirt and oxidation buildup.	1. Use teflon insulated wire enclosed in ceramic insulating beads. 2. Use ring type terminal connector rather than spade type. 3. (a) Use better support for electrode; heavier gauge rod or different design. (b) Require periodic cleaning of electrode with steel wool or emery paper. Move electrode farther away from source of heat or use material more resistant to surface oxidation than copper. 4. Use electrical pilot light in thermocouple circuit or make pilot light visible without looking into combustion bowl. Conversion to electrical ignition system appears desirable.
Exhaust Flue	1. Air flow generally "reversed" upon ignition. 2. Outer stack too hot to touch--a burn hazard.	1. Use compressed air line for induction (impractical for marine use) or install powered blower. 2. Use insulated ducting or box flue in insulated cabinet.
Burner and Burner Controls	1. Response delay of gas cock safety valve shutoff too long after flame-out, e.g., continuous gas flow times of 34 seconds and 39 seconds were measured after flame extinguishment. Upon next attempted ignition, residual unburned gas in combustion bowl flashed flames into operator's face.	1. Use different valve and/or thermocouple circuit or change position of thermocouple. <u>This is a very serious safety consideration that must be corrected.</u>

Propane Toilet (contd.) Problem Area	Problem	Possible Solution(s)
Burner and Burner Controls	2. Foaming and frothing of (real) boiling urine adversely affected performance.	2. Protect burner and pilot orifice from salt deposits by relocation or protective screen. Secondary air flow through combustion bowl may also help. Periodic cleaning, especially of pilot orifice, may be required.
	3. Paper and solid deposits interfered with burner (even with no overload), i.e., obstructions had to be manually removed from in front of burner before ignition was possible.	3. Relocate burner, redesign bowl shape or reduce recommended capacity.
	4. Burner assembly appeared generally degraded at the conclusion of the test program. Doubts are raised as to its expected working life and durability.	4. Continue long term testing for further observation. Consider redesign, relocation and different materials.
	5. Removal of burner assembly for inspection and maintenance was a difficult procedure.	5. Redesign for easy removal.
	6. Main burner air inlet was not enclosed in the outer flue, i.e., combustion air was drawn from the vicinity of the toilet itself and not down through the flue.	6. Makeshift cover was fabricated over the air inlet and communicated to the outer flue by cutting holes in the mounting plate (Fig. 9). This should be redesigned for minimally restrictive air flow from the flue to the venturi.
Combustion Bowl	1. Makeshift splash guard moved out of place occasionally and eroded (almost completely) during combustion cycles.	1. Make guard integral with combustion bowl and use high-temperature resistant material.
	2. Residual ash caked onto combustion bowl and cleaning was difficult.	2. Make combustion bowl as accessible as possible for cleaning with a scraper.
	3. Surface condition of combustion bowl shows signs of deterioration.	3. Continue long term testing for further observation.

Propane Toilet (Contd.)

<u>Problem Area</u>	<u>Problem</u>	<u>Possible Solution(s)</u>
Combustion Bowl	4. Combustion bowl opening judged too small for easy passage of toilet bowl liner, toilet paper and waste Material.	4. Design larger bowl opening.
Toilet Bowl and Cabinet	1. Exposed outer surfaces were generally too hot during operation. 2. Feet melted on toilet seat and cover. 3. Toilet bowl and seat took on scorched appearance.	1. Use more and better insulating material between combustion bowl and cabinet and consider flow-through ventilation. 2. Replace with high-temperature resistant material. 3. Use high-temperature resistant paint and plastic (correction of above Item 1 may alleviate this).
Odor	1. Odor problem with real wastes was severe. The odor appears early in burn cycle and seems to arise predominantly from the urine.	1. Develop effective catalyst bed for flue.

Diesel Oil Toilet

<u>Problem Area</u>	<u>Problem</u>	<u>Possible Solution(s)</u>
Burner and Burner Controls	1. Electronic Controls were generally erratic and unpredictable in performance.	1. May have been due to breadboard construction and some loose connections--troubleshooting is needed.
	2. Burner performance was very erratic and difficult to adjust. Numerous "flashes of fire" from atomized fuel particles in the combustion bowl and exhaust flue occurred as the burner randomly ignited and extinguished.	2. More basic consideration needs to be given to the choice and design of the burner nozzle and optimum fuel and air adjustments.
	3. The delicate nature of the Sonicores nozzle cup and the precision alignment required made this unit difficult to adjust and easily broken. Removal and installation of the burner into the toilet was a delicate operation.	3. Select a more rugged burner nozzle or redesign the system so that the present burner can be used with greater facility.
	4. The heat sensing switch installed in the exhaust flue delayed too long in sensing a flame-out. This allowed too much unburned fuel to collect in the combustion bowl before the ignition system was re-activated.	4. Replace with more responsive heat switch and/or relocate the switch closer to the burner or hot exhaust flow, e.g., the outer casing.
Exhaust Flue	1. A large flow of secondary air through the combustion bowl was necessary for operation of the burner. The compressed air line had to be left on continuously.	1. Install powered blower for secondary air supply.
Fuel Supply	1. Suction feed in the fuel line was not sufficient for satisfactory burner operation. Gravity feed was needed and fuel supply had to be elevated above toilet.	1. Consider adding fuel pump, especially if toilet is to be installed above and at a distance from a boat's fuel tank(s).

Diesel Oil Toilet (contd.)

<u>Problem Area</u>	<u>Problem</u>	<u>Possible Solution(s)</u>
Motion Tests	1. Attempts to operate the diesel oil toilet under motion were unsuccessful.	1. General performance must be improved before the test program can be resumed.
Odor	1. The noticeable odor of burning diesel fuel was always present regardless of load. The unpleasant hot urine odor was not as strong as it was with the propane toilet. There may be a synergistic action with the fuel odor.	1. Test of catalyst bed in the inner flue produced nebulous results. Subjective reaction to odor among several people did not change with or without the catalyst.

Wind Effects Test

An evaluation of the effects of a 40 MPH wind across the top of the flue had originally been scheduled for both toilets. After the excessive delay of the gas cock safety valve shutoff on the propane toilet was discovered, it was judged too hazardous to perform any further testing which might cause a flame-out and let a significant amount of unburned propane collect in the hot combustion bowl or escape to the room (an explosion potential). This test was not conducted.

The wind test (and all others) on the diesel oil toilet was postponed until the basic operational difficulties can be corrected.

Residual Ash Ratios and Ash Capacity

Determination of the ratio of residual ash to initial waste matter proved to be somewhat difficult to accomplish. We had hoped to be able to remove the accumulated ash of twenty burn cycles and average out the ash contribution per cycle. This would also have allowed us to assess toilet performance as ash build-up accumulated in the combustion bowl. Time did not permit, however, more than nine full incineration cycles, five of which each contained 794 gm of synthetic feces and 159 gm of toilet paper. A total of 4,765 gm of solid material was, therefore, burned during the synthetic runs plus an unknown quantity of real fecal matter, toilet paper and bowl liners deposited during six defactions into the toilet. The weight of the accumulated ash removed from the toilet was 140 gms, however, due to the difficulty of cleaning ash from walls, this weight is by no means quantitative and should probably be quite higher. As a rough estimate though, we may divide 4,765 gm solid input by 140 gm accumulated ash to obtain a ratio of 34 parts initial waste material to one part ash (or one part initial waste to 0.029 parts ash). See commentary, Note 5.

It is suggested that any further toilet testing include additional determinations of ash ratios and ash capacity for the sake of verification and completeness, respectively.

Analytical Analysis

Analytical analysis of the effluent components was carried out on both the exhaust gas and the residue ash. The methodology has been discussed in the previous section and the results appear in Tables 6 and 7. Exhaust gas samples were taken and analyzed (for both toilets) toward the beginning (0.5 hrs.) and toward the end (2.0 hrs.) of an incineration cycle.

The composition changes significantly in the case of each toilet as can be seen in Table 6 (the results of two analyses on successive samples taken within one minute of each other appear together). As a rule, the oxygen concentration increases, the nitrogen concentration remains the same and the carbon monoxide, carbon dioxide and hydrogen percentages all decline in the 1.5 hours between sampling times. This is all expected as the oxidation of the waste material progresses. The concentrations of CO measured at 0.5 hours (0.95% to 1.86%) are fairly high for this gas and would pose a lethal hazard potential should the flue leak or become clogged in an enclosed space. At 2.0 hours, when most of the incineration is presumably complete, the CO level drops below 100 ppm and based on this, we feel that both units would be in compliance with UL Subject 1150, Section 2.9.9 which requires that the carbon monoxide concentration be below 0.04% (400 ppm) when the toilet is burning with no charge.

The flue gases were quite smoky and contained, from qualitative examination of filters, a moderate amount of particulate material. Smoke output appeared to be variable during a combustion run. Flue gas was free of coliform bacteria.

The ash contains a high content of water insolubles; the soluble material gives a strongly alkaline solution probably due to alkali metal oxides in the residue. Loss on ignition is extremely high in view of the relatively low total carbon values. A thermal gravimetric analysis was done on residue data and show a continuous marked loss in sample weight over a 25-minute period above about 700°C. Heating was done at 18°C/min. in this range. From this measurement it is concluded that the residue obtained from the combustion toilet is thermally unstable and that the high temperature volatile components are not carbonates, water or alkali halides. It is possible that combustion conditions result in a large percentage of nitrates and possibly sulfates whose decomposition and volatilization is being detected in the loss on ignition and thermal analyses. This could be confirmed by nitrogen and sulfur analyses; such analyses should be included in any future testing work. The ash samples were also essentially free of coliform bacteria.

TABLE 6

ANALYSIS OF FLUE EXHAUST GAS

Toilet	Load	Samples Time, Hr.	Components					% Total Hydrocarbons
			% O ₂	% N ₂	% CO	% CO ₂	% H ₂	
Propane	5425 ml synthetic urine	0.5	14.2	79.5	0.95	4.01	0.47	0.17
	2166 ml real urine		14.7	79.1	1.86	3.17	1.17	0.30
Propane	794 gm synthetic feces	2.0	18.6	78.2	N.D.	2.25	-	0.03
	159 gm toilet paper		17.8	78.7	N.D.	2.34	-	0.04
Propane	4000 ml real urine	2.0	18.6	78.2	N.D.	2.25	-	0.03
	3576 ml synthetic urine		17.8	78.7	N.D.	2.34	-	0.04
Diesel Oil	4 real defactions 4300 ml real urine	0.5	10.6	81.1	1.50	6.42	0.68	0.16
	5 real defactions 4300 ml real urine		10.9	81.6	1.57	6.06	0.53	0.11
Diesel Oil	4 real defactions 4300 ml real urine	2.0	16.3	80.4	6.55 ppm	4.07	-	0.01
	5 real defactions 4300 ml real urine		16.1	80.5	90 ppm	3.90	-	0.00

Sample time refers to the period from the start of the burn cycle to the point of sampling.
 % O₂ includes any argon present.
 N.D. = none detected. CO sensitivity for this analysis > 100 ppm.

TABLE 7

ANALYSES OF RESIDUE ASH AND FLUE GAS

<u>Ash Analysis</u>	<u>Run I</u>	<u>Run II</u>
	<u>Propane Toilet</u>	<u>Diesel Oil Toilet</u>
Total Carbon %	0.10	0.78
Loss on Ignition %	11.2	32.8
Insoluble %	58.4	Not Done
Coliform Count* No/gm	0	1**
<u>Exhaust Gas</u>		
Reflectance ⁺ % control	8.4	56.4
Coliform count ⁺⁺	0	9

* 2 gm samples of ash mixed with 100 ml phosphate buffer and supernatant assayed for Doliforms by Millipore Filter procedure.

** 1 Coliform colony obtained with 2 gm sample

+ Run I sampling time--10 minutes
Run II sampling time--3 minutes

++ See experimental procedure--page 6

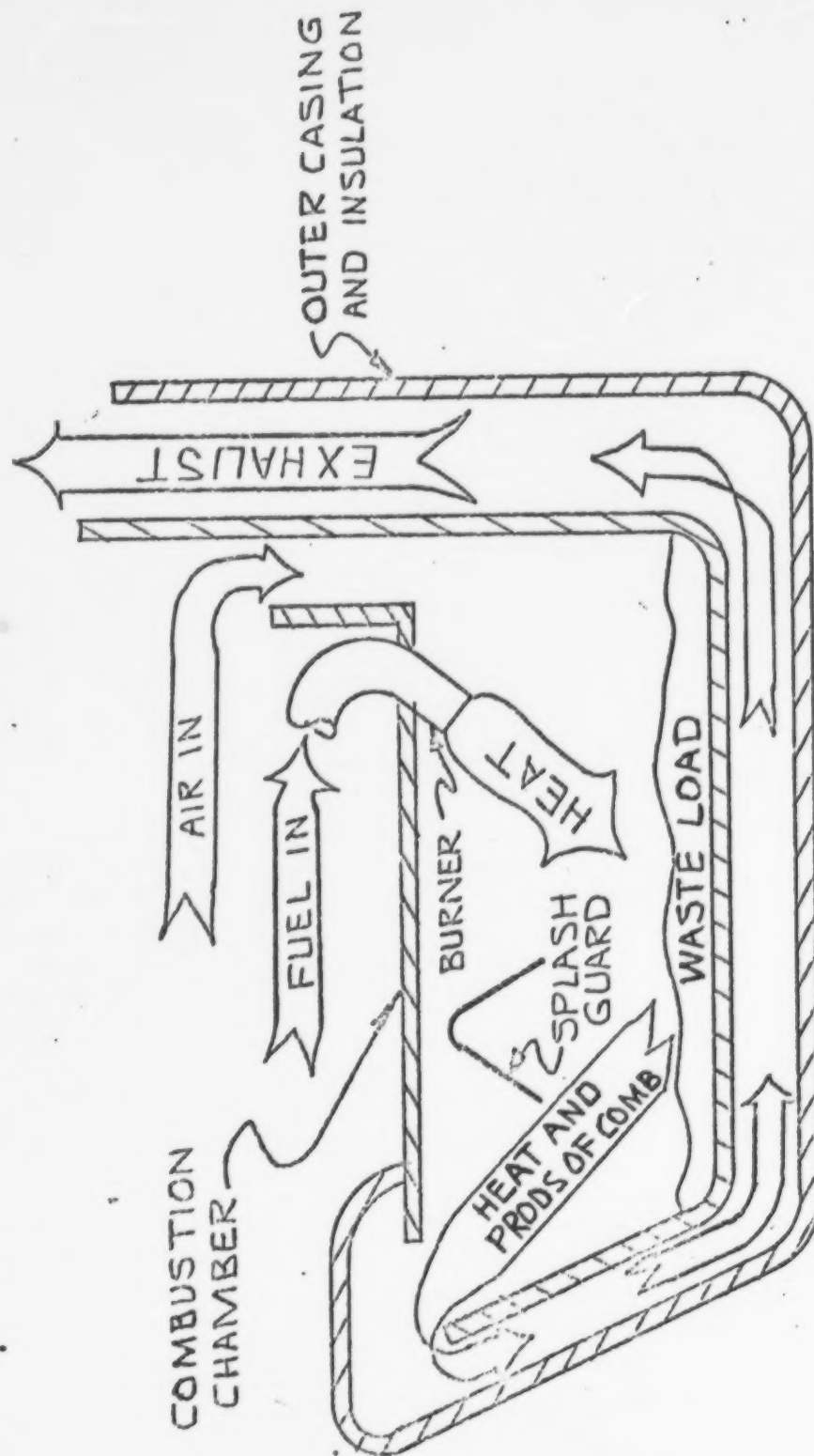


FIGURE 21
SCHEMATIC OF DOUBLE PASS
SYSTEM

Safety Analysis

The UL Subject 1150, Section 3.7.2.2 ignition test was carried out according to the procedures outlined earlier. Figure 10 shows the placement of the spark plug before the test (prior to closing the combustion chamber) and Figure 9 portrays the closed explosion box. Gas chromatography results on two successive samples taken from the box prior to the first test showed propane (in air) concentrations of 2.8% and 2.4%. When the spark circuit was closed, we heard, apparently simultaneously, a muffled boom and the sound of the box cover clanging back down on the box. Examination of the apparatus showed that only the cover was sitting on the box slightly askew. The box and the toilet were not visibly damaged in any way. One concludes however, that an ignition source in the closed combustion bowl is capable of igniting a flammable mixture surrounding the toilet and that the unit fails to meet the UL specification.

The test was repeated for verification and the propane concentration was increased. Gas analysis results were 4.2% and 3.9% propane in air. When the spark circuit was turned on, there was another immediate but much stronger reaction. After a very loud explosion, one heard the sound of breaking glass followed by the clanging of the box cover as it hit the floor. Post-test examination (Figure 11) showed that the box had bulged noticeably on two sides and had split open one of its welded corner seams halfway down the entire length. The cover had apparently blown all the way to the ceiling and smashed two floodlights directly above it - the light fixtures themselves were also destroyed. On the way down, the cover apparently hit one of the solenoid valves as one had rotated on its nipple to a downward facing position (compare Figure 9 with Figure 11). The toilet flue had lifted off its base and was resting against the wall at a sharp angle. The box cover, which was fitted tightly around the flue, had obviously wrenched the flue out of position when it blew off. The toilet bowl and seat had been removed after the first test in order to inspect the combustion bowl for damage. These had been left off for the second test which, undoubtedly, had allowed a large piece of the upper combustion bowl insulation to break off (Figure 11) during the explosion. The combustion bowl, burner and toilet cabinet did not appear to be damaged but this is not surprising when one considers that the bulk of the exploding propane is not in the bowl but in the box surrounding the toilet.

The second test reconfirmed the conclusion that the propane toilet failed to meet the requirements of the UL ignition test. These specifications are set forth in Section 3.7.2.3 quoted below:

2.7.2.3 There shall be no ignition of the flammable mixture surrounding the assembly. The results of the above procedures shall show that the assembly is sufficiently tight to exclude flammable vapors or capable of operating within an explosive atmosphere, without igniting same, or that the assembly is so constructed that, if an internal explosive mixture is ignited, it will not ignite an explosive mixture surrounding the device.

The toilet has probably failed the above test due to gas leakage and communication from either or both of its two openings: the main entry hole or the hole for the flue connection. The connection between the combustion bowl and outer casing to the flue base is presently a rather loose fitting insert. One can see how this may be improved by decreasing tolerance (to create more of a "force-fit") as well as introducing high temperature resistant gasketing and sealing materials such as asbestos and fiberglass. This connection should be made more or less permanently during construction as long as the burner assembly can still be removed in the field. Improved sealing of the combustion bowl hatch closure shall prove to be more difficult as freedom of movement is basic to the toilet's operation. Here again, high temperature resistant gasketing materials between bowl and closure may help as would a mechanical latching device to obtain and hold a tight fit. See commentary, Note 6.

Summary and Conclusions

The two month testing program on the two prototype combustion toilets has brought out numerous difficulties associated with the general performance and reliability of the units. Each device required a great deal of attention during its operation and even then it was sometimes difficult or impossible to coax it into doing the job it was created for. The basic operational problems have been laid out in tables contained in the previous section and they need not be reiterated here. Some of these problems, as we have said, may be those associated with the testing of the first prototype of any complex new design and they may be easily resolved with some additional time and effort. Some, indeed, are quite minor and may just be related to the breadboard construction. These would resolve themselves during the manufacture of production models. Other problems, however, like the failure of the UL ignition test require careful thought about the basic design of the toilet and whether it can be modified to meet the requirements or whether one must start all over again at the drawing board. All these problems have added up, however, to make both units impractical and not recommended for further marine evaluation without the certain basic improvements previously discussed. A good deal of attention must also be paid to the correct interpretation and compliance with Underwriters' Laboratories' Subject 1150, "Requirements for Marine Sewage Incinerating Devices". Any commercial model will, undoubtedly, have to meet this specification and the present prototypes are questionable in several areas (we have not even conducted all the tests described in this 21 page standard, e.g., vibration test, shock test, direct current test (diesel oil toilet), high ambient temperature test, chemical resistance test and low ambient temperature test. A thorough work-up of the UL tests would be desirable as soon as an adequate working model is constructed.

Conceptually, we still feel that the incineration approach to on-board waste treatment is sound. This principle has met with commercial success for mobile land application and we have demonstrated that the additional parameters of water motion does not pose insurmountable obstacles. It is advisable, at this point, to continue the development program for both models and correct the deficiencies borne out by this test study. In retrospect, we also feel it desirable to conduct the development and testing more hand in hand to prevent going too far down the wrong tract. Unfortunately, geographical and organizational differences make this difficult but a lot stands to be gained if a suitable arrangement can be worked out.

Acknowledgement

We wish to thank Dr. G. F. Doebbler for his assistance in performing various aspects of the analytical analysis.

Engineering Commentary on Evaluation Report

The following comments indicate engineering response to recommendations arising from the evaluation tests, and in some cases are intended to clarify whether a particular aspect of the test model was inherent in the design, or was a peculiarity of the model or of the test setup.

1. The description of the motion test procedure makes mention of guy wires and loosened sheet metal screws. It should be understood that both the guy wires and the screws were expedients for the test setup, to provide support for the stack that would normally be provided by deck or bulkhead penetrations.

2. The description of the fuel consumption procedure mentions the necessity of gravity feed of the fuel oil. Earlier experimentation done at the Reston workshop indicates that gravity feed should not normally be necessary. However, the addition of a positive-acting fuel shutoff valve in compliance with Coast Guard recommendations will make it feasible to locate the fuel tank so that there is a positive fuel pressure due to gravity.

3. Fuel consumption measured was reported as 1.7 lb per hour or 4.25 lb per 2-1/3 hour burn. This was contrasted with a figure of 0.36 - 0.4 lb per burn cited in the proposal. The proposal figure was in error, and was not consistent with the 25,000 Btu/hr figure also cited in the proposal. 25,000 Btu/hr is equivalent to about 1.27 lb per hour, about 75% of the consumption rate measured in the tests.

4. The following comments follow the sequence of the "problem area" table included in the evaluation report.

Propane Toilet

<u>Problem Area</u>	<u>Problem</u>	<u>Comment</u>
Ignition System	1-4	The manual ignition system is being replaced by an electronic system. Improved ducting will assure that electrodes are in a cooler environment. Improved insulation and terminal connectors are part of the original intent.

<u>Problem Area</u>	<u>Problem</u>	<u>Comment</u>
Combustion Bowl	1	The original intent has been to make any splashguard an integral part of the combustion bowl. Because of the cut-and-dry nature of designing the guards, it was necessary to make the trial guards as lightweight, removable pieces.
	2	It should be noted that the caking effect and buildup on the bowl seemed peculiar to the synthetic urine and feces. The residue of actual feces was a loose ash. Even with synthetics, the caking phenomenon has only been observed in the burns made at Tarrytown. It may be that this is a result of the fact that the initial batches of synthetic urine, mixed by the engineering department, lacked some of the specified chemicals which were not available at the time.
	3	Deterioration was not evident when the teardown inspection was made. Sharp projections and corners on the cast surface chamber in the hottest area remained sharp. The reduction in combustion temperature that will be permitted by the use of a catalyst should end any likelihood of deterioration.
	4	The opening in the hopper directly above the combustion bowl opening was considerably smaller than the latter. In separate trials with a larger hopper opening, the combustion bowl cover seems adequate, but it can be enlarged if it proves necessary.
Toilet bowl & cabinet	1,3	It is intended to ventilate the cabinet. Lowered combustion temperatures will further alleviate the problem.
Odor	1	Tests at the LaMere Laboratory indicate that a catalyst bed will be effective.

Diesel Oil Toilet

<u>Problem Area</u>	<u>Problem</u>	<u>Comment</u>
Burner & Controls	1	As stated.
	2	Ducting of secondary air will stabilize the flame and keep the nozzle from overheating.
	3	Will be installed on a removable panel interchangeable with propane system.
	4	Use of catalytic oxidizer and air ducting will permit closer regulation of temperature.
Exhaust flue	1	As stated.
Fuel Supply	1	A positive shutoff valve, installed in compliance with Coast Guard recommendations in combination with gravity feed, if necessary, can be used in lieu of a pump.
Motion tests	1	The problem seemed to trace to air turbulence set up by the displacement of the sloshing wastes. Secondary air ducting should eliminate this problem.
Odor	1	Others did notice a difference. The catalyst was particularly effective on the propane unit, but was not tested on it at Tarrytown.

5. The description of residual ash ratios and ash capacity notes that it was difficult to clean ash from the walls of the chamber. This has not been noted in previous experience, and may be a peculiarity of the composition of synthetic feces used.

6. The teardown inspection revealed a construction discrepancy that provided the most likely leakage path to permit propane gas to reach the ignition source. The exhaust cover that forms the flue passage around and beneath the combustion chamber

did not conform to the shape of the combustion chamber cover. As can be seen in Figure 12, the exhaust cover has a square corner at the back, with the radiused corner of the chamber cover circumscribed in it. The result is a hole of about 1 square inch at each corner. This was concealed by insulation prior to the test, but the insulation was loose, and too permeable to form a seal.

All seams and mating surfaces are designed to be of a closer fit than the minimum gap through which a propane flame can propagate. However, as an added precaution, fixed, flexible gaskets are being designed in at each mating surface of the combustion system, and the flushing lid is being designed to travel in a dovetail type of track so that it cannot be forced open by internal pressure.

7. In the summary of the evaluation report, it is noted that certain tests specified by Underwriters Laboratories have not been conducted.

One of these, the low ambient temperature test, was to have been done, had weather and time permitted. The others in general are structural and environmental tests appropriate to a production prototype but not to a laboratory model. It is intended to perform such tests on the production prototype.

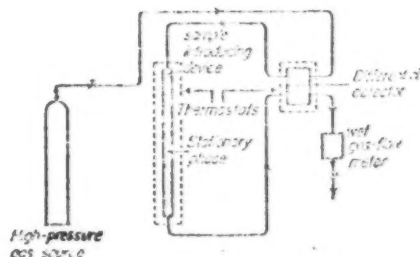
APPENDIX E

Analysis Procedures for Gas Products

The analysis of gas products for the combustion toilet was done using gas chromatography.

In gas chromatography a sample mixture (taken from the gaseous effluent of the combustion toilet) is introduced into the front end of a gas chromatograph column. The column consists of a tube filled with a stationary bed of a solid (typically) of large surface area. The column is maintained at a constant temperature and a constant flow of an inert carrier gas is passed through it. This gas, the "eluent", transports the components of the mixture in gaseous or vapor form through the column. Since the components are retained by the stationary phase to different degrees, their effective speeds in flowing through the column, therefore, differ. The column is sufficiently long, so that when the components of the combustion toilet effluent mixture emerge from the outlet end, they emerge as individual "bands" separated by zones of the carrier gas. Composition of the effluent is then sensed by a delicate detecting device, capable of indicating the presence of the components qualitatively and quantitatively. In the gas analyses for the combustion toilet either thermal conductivity or flame ionization detection were used as the detecting devices.

The figure below shows a diagram of the gas chromatography apparatus.



For the combustion toilet project a number of different column sizes, stationary bed materials, temperatures, carrier gases, and detectors were used. The specific types used depended upon which gaseous product was being analyzed. Table 12 gives the specifications for the chromatography columns used.

The specific hardware used were the Hewlett Packard 7600 Series, F & M 700, Varian 1800, and Varian 1700 gas chromatographs.

As indicated in Table 8, gas analyses were conducted for oxygen and argon, nitrogen, carbon monoxide, carbon dioxide, C₁ through C₆ hydrocarbons, total hydrocarbons (C₁ through C₂₀ hydrocarbons), and hydrogen.

TABLE 8

SPECIFICATIONS FOR GAS CHROMATOGRAPH COLUMNS

Product Being Analyzed	Column Packing Material	Column Size	Temperature	Carrier Gas	Detector Type
Oxygen + Argon	5 A Molecular Sieve	1/4" x 6'	Isothermal 60° C	Helium	Thermal Conductivity Detector
Carbon Dioxide	Carboseive B	3/16" x 4'	Isothermal 60° C	Helium	Thermal Conductivity Detector
C ₁ through C ₆ Hydrocarbons	NC ₈ /Parasil	1/8" x 12'	Isothermal 110° C	Nitrogen	Flame Ionization Detector
Total Hydrocarbons (C ₁ through C ₂₀ Hydrocarbons)	3% OV-1	3/16" x 4'	Isothermal 300° C	Helium	Flame Ionization Detector
Hydrogen	5 A Molecular Sieve	1/4" x 5'	Isothermal ambient room temperature	Nitrogen	Thermal Conductivity Detector

APPENDIX F

TEARDOWN INSPECTION

1. Cabinet panel around duct has a wrinkle and scorched area extending radially out from duct clearance hole.
2. Cabinet back panel has a collection of metal scale on its lower flange that apparently has fallen from the drain hole in the exhaust cover.
3. Burner mounting plate is out of flat with respect to transition duct by about 1/8". This is a possible gas and flame-front path. Out of flat may have been due to warping when the burner mixing shutter had a box welded over it to isolate it from the boat atmosphere.
4. Pilot burner and thermocouple tubing and mounting brackets have considerable metal oxide scale.
5. Insulation is loose on transition duct.
6. Seat is scorched and cracked. Plastic feet are melted.
7. Bowl is scorched.
8. Front/side cabinet is scorched at top front edge and has a heavy soot mark on right side (as one faces the toilet) about beside the rear leg.
9. Insulation is loose at front and back of exhaust cover and is missing from top in front of closure.
10. Two front top mounting bolts (frame/cover) broke when being disassembled. Lockwasher under one of them broke.
11. Frame shows heat marks at two front casting support points.
12. Exhaust cover is heavily scaled all around and has a double handfull of loose scale inside.
13. Gap between exhaust cover and combustion chamber cover was about .010 - .015 inches, and about .050 around the front corners, but there is a one-inch right triangular gap at each back corner, because the combustion chamber cover has round corners that are inscribed in the square corners of the exhaust cover. This may have been the critical leakage path on the ignition explosion.

APPENDIX G

Odor Control Program

Odor control is generally handled by three classified methods: adsorption, absorption, and incineration.

Adsorption is a method of mechanically attaching particles of a gas or vapor to a surface. This surface (e.g., pellets) can be chemically treated to oxidize the captured odor or gas, thereby, eliminating a recharging step.

Absorption is a method to combine the odor molecules into an emulsion or a chemical solution. This is accomplished by the spray method (scrubbing). Sprays may be accomplished by an oxidizer to prevent the spray water from becoming saturated with pollutants.

Incineration can be achieved by direct flame combustion or catalytic combustion. Direct flame combustion requires high temperatures (e.g., 1000°F to 1500°F) with holding times in the order of one half to three quarters of a second. Catalytic combustion takes place at temperatures between 500°F to 1000°F.

Three methods of odor control were evaluated: Adsorption, direct flame incineration and catalytic oxidation. Absorption was not considered since the media through which odor bearing gases must pass is relatively dense. Along with other drawbacks the treatment bed presents too great a flow restriction.

A standard charge was used to evaluate the effectiveness of each type of odor control. A standard charge consisted of 226 grams of slurry made from:

- 1 can of dog food (7.75 oz.)
- 1 quart of water
- 12 feet of toilet tissue
- 1/2 teaspoon of salt
- 1/2 teaspoon of soap powder
- 1/2 teaspoon of vinegar
- 4 cc's of skatole

These ingredients were mixed in a blender and inserted into the combustion chamber. Burner efficiency tests were conducted. The first utilized a burner with a standard orifice (#53 drill size), a standard charge was reduced to 6.6 grams of ash in 12 minutes. The fuel consumed was measured at 1.95 cubic

feet of gas with a rating of 2516 btu's/cu.ft. The air required for complete combustion for one cubic foot of gas is 23.8 cu. ft.

$$23.8 (1.95) = 46.5 \text{ ft}^3\text{-AIR}$$

$$\frac{46.5 + 1.95}{12} = 4.04 \text{ ft}^3/\text{MIN}$$

The theoretical flow of products of combustion is approximately four cubic feet per minute. This amount of gas will be treated when a #53 orifice is used.

Additional tests were conducted with various sizes of orifices. One such test using a small orifice (#56 Drill Size) was conducted and burned for 18 minutes. During the combustion cycle two cubic feet of gas were consumed producing 6.7 grams of ash from a standard charge of waste.

Direct flame incineration testing was conducted with the equipment arranged as shown in Figure 23. A standard straight Bunsen type burner was inserted at the bottom of the stack. The gases exhausted from the combustion chamber were heated by the open flame in the stack. Various orifice sizes were tried in the burner; an orifice permitting a flow rate of gas burning at the rate of 4,000 btu's per hour was finally used. This type of incineration was reasonably effective after the stack reached a high temperature, but did not control odor in the early burning state. Some negative features of this type of odor control are: the need to monitor two flames or the difficulty involved with splitting the main flame into two parts, one for waste and one for odor. An additional negative feature is the high stack temperatures required with this type of odor control.

Catalytic oxidation was conducted with the equipment arranged as shown in Figure 24. The catalyst used was of the precious metals type. A colloidal slurry deposited on a ceramic honeycomb substrate. The catalytic units were cylindrical (3-7/8 OD x 1 inch thick) in shape to fit within the exhaust stack. The stack was altered so the number of discs would be changed to evaluate the effectiveness of a specific number of units. Five units or discs were first installed in the stack and tested. The five inch total stack reduced the odors well below the objectionable level. The discs were removed one at a time and a burning test conducted with each change. Under the conditions which were operated, three discs (3 inch stack) seemed to be the minimum number of which would control odor. The method of judging the effluent was qualitative in nature. Several people sniffed the effluent and made a judgment. Of

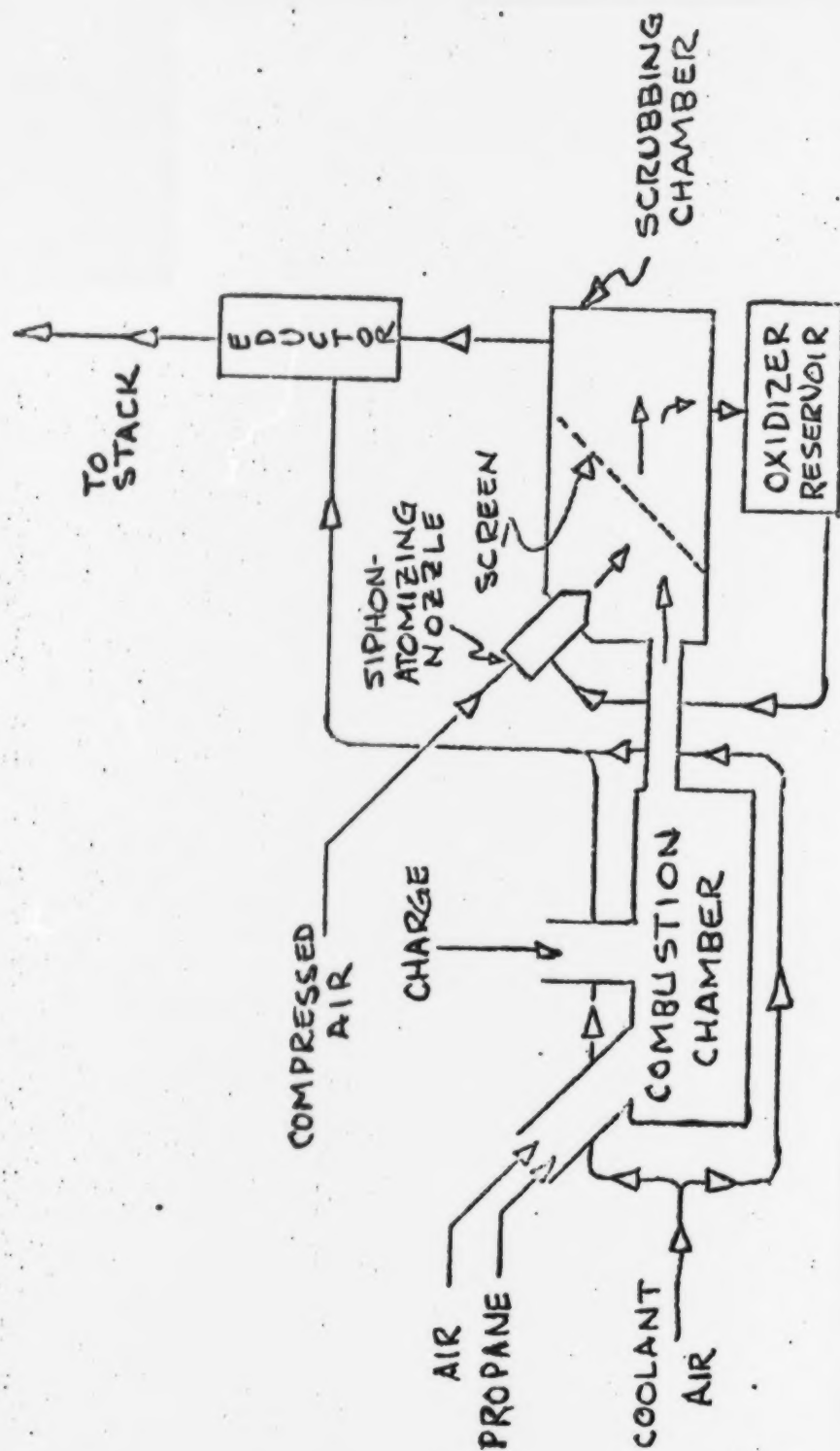


FIGURE 22. ODOR CONTROL: ADSORPTION - CHEMICAL TREATMENT

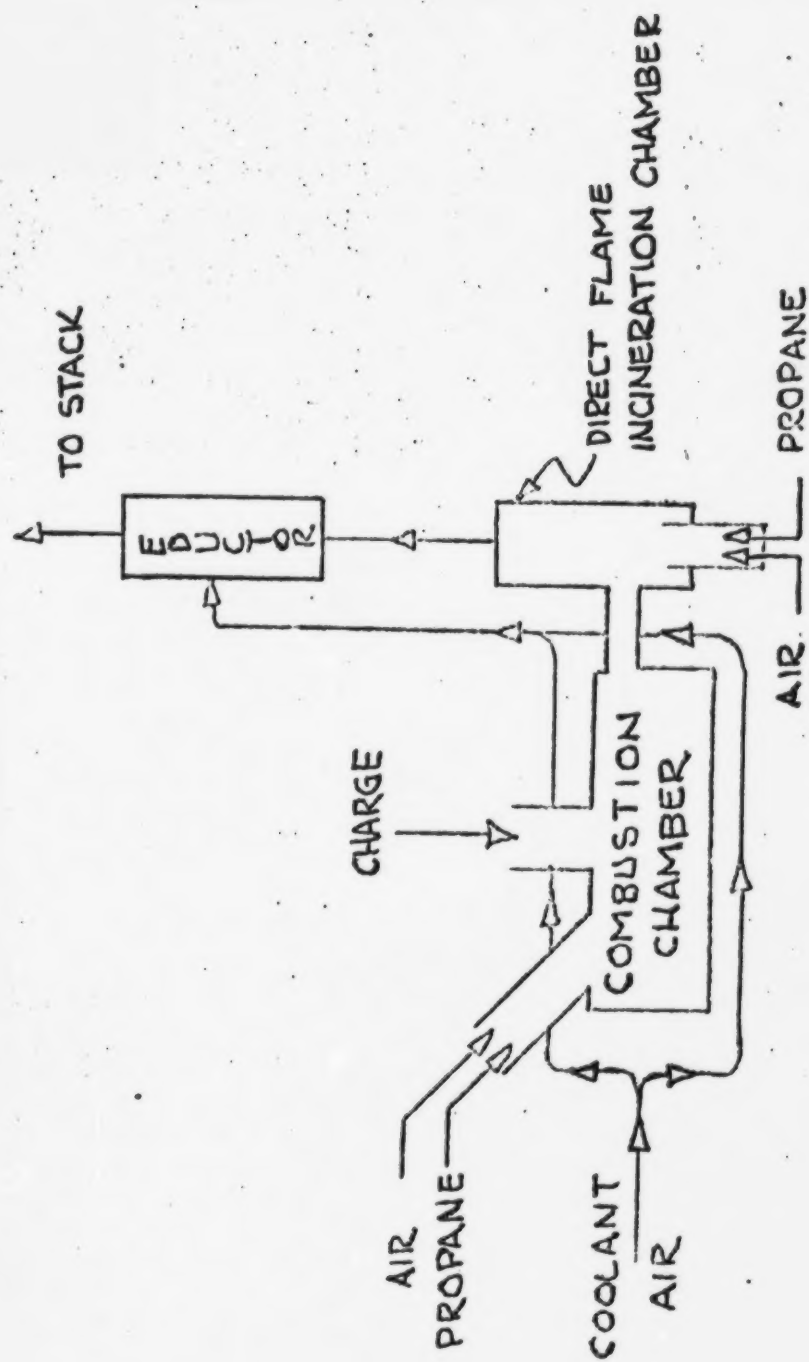


FIGURE 23. ODOR CONTROL: DIRECT FLAME INCINERATION

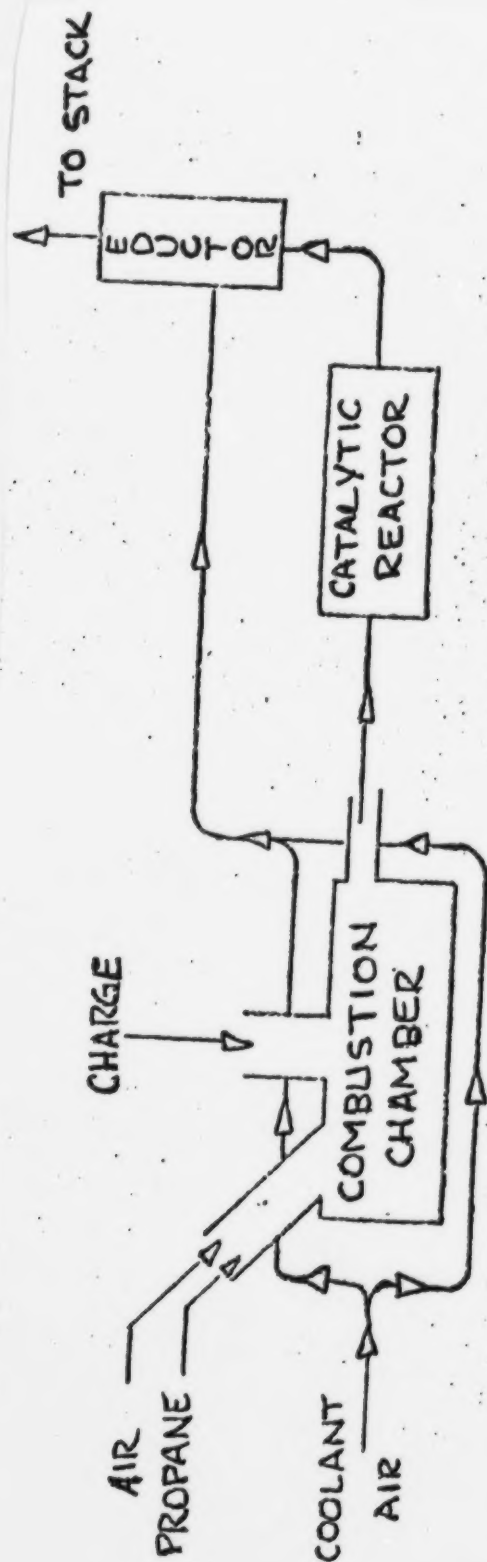


FIGURE 24. ODOR CONTROL: CATALYTIC INCINERATION

the three methods tested the catalytic method is the most promising. The total exhaust gas volume must be kept to a minimum to keep the size of the catalyst within an economical boundary. Additional testing will be conducted using new catalysts. The temperature rise across the lead will be monitored to obtain a measure of the combustion taking place within the catalytic stack.

APPENDIX H

MOTION TABLE

Evaluation of the toilet's suitability for installation on a boat requires that it be operated while undergoing roll and pitch motions of varying periods and amplitudes. To accomplish this under simulated conditions a motion simulation table was built.

The table supports the toilet on a platform that is pivotable on a centrally mounted spherical bearing. Vertical oscillations are imparted independently at two mutually perpendicular horizontal axes of the platform by means of gearmotors and crankarms. The variable speed of the gearmotors permits roll and pitch period to be varied, while the throw of the crankarm can be varied to change roll and pitch amplitudes. Variations of from 3° to 15° positive amplitude and from 4.5 to 1.6 second periods were used for the evaluation.

Power requirements of the table are shown in the following analysis. The construction of the table is shown in the drawings listed in Figure 25.

Fifteen detailed drawings following the list in Table 25 (on original report pages 187-201) have been withdrawn because they are not reproducible.

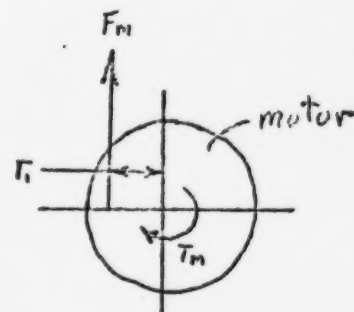
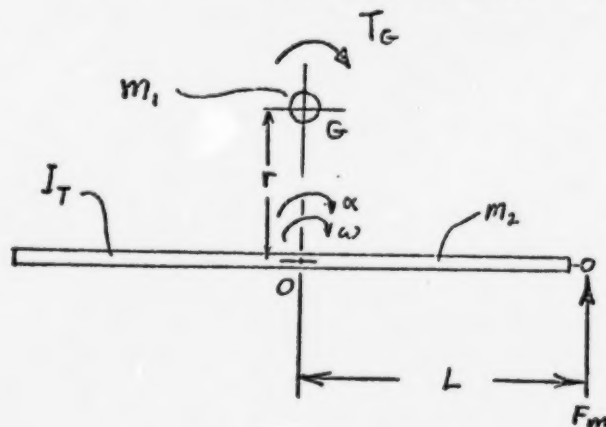
POWER REQUIREMENTS FOR MOTION TABLE

These calculations were used to size the power system for the motion table. Elaboration on the basic $\pm 15^\circ$ x 4 sec period design has been made because the table, per these specs, would not match the accelerations expected onboard most small craft; 0.5 g's maximum. The tests should go as follows:

$\pm 15^\circ$ at accelerations varying between 0.1 and 0.5 g's. This means that the periods will be shortened as required to meet the anticipated onboard dynamics.

Force Analysis - Motion Simulation Table

Waste Treatment 74049



$$\Sigma T_O: I_T \alpha + (I_G + m_1 r^2) \alpha = F_m L \quad (1)$$

$$F_m = T_m / r_1 \quad (2)$$

Combining (1) and (2):

$$\frac{T_m L}{r_1} = (I_T + I_G + m_1 r^2) \alpha \quad (3)$$

$$T_m = \frac{63000 \text{ hp}}{n} \quad (4)$$

Where

$$n = \text{rpm of motor}$$

Combining (3) and (4)

$$\alpha = \frac{63000 \text{ hp } L}{nr_1 (I_T + I_6 + m_1 r^2)} \quad (5)$$

also

$$a_{6 \tan} = r\alpha \quad (6)$$

Combining (5) and (6)

$$a_{\max} = \frac{63000 \text{ hp}_{\max} L r}{nr_1 (I_T + I_6 + m_1 r^2)} \quad (7)$$

$$\text{Let } I_6 = 0$$

$$m_1 = 200 \text{ lb}_m$$

$$r = 12 \text{ in}$$

$$r_1 = 5 \text{ in}$$

$$I_T = m_2 \left(\frac{L}{2}\right)^2 = 4050 \text{ lb}_m \text{ in}^2$$

$$L = 20 \text{ in}$$

Then equation (7) becomes

$$a_{\max} = 92 \frac{\text{hp}_{\max}}{n} \quad (8)$$

Now

$$\alpha = -W^2 \sin WT$$

$$\alpha_{\max} = W^2 \quad (9)$$

$$W = 2\pi f \quad (10)$$

$$f = \text{rpm}/60 = n/60 \quad (11)$$

Combining (10) and (11)

$$W = \frac{\pi n}{30} \quad (12)$$

Combining (9) and (12)

$$\alpha_{\max} = \left(\frac{\pi n}{30}\right)^2 \quad (13)$$

From equation (6)

$$a_{\max} = r \alpha_{\max} \quad (14)$$

Combining (13) and (14)

$$a_{\max} = r \left(\frac{\pi n}{30}\right)^2 \quad (15)$$

If $a_{\max}$ is to be expressed in g's, equation (15) becomes

$$a_{g_{\max}} = \frac{r}{12g_c} \left(\frac{\pi n}{30}\right)^2 \quad (16)$$

$$\text{or } n = \frac{30}{\pi} \sqrt{\frac{a_{g_c} 12}{r}}$$

$$\text{Let } a_{g_1} = 0.1 \quad \Rightarrow \quad n_1 = 17 \text{ rpm}$$

$$\text{Let } a_{g_5} = 0.5 \quad \Rightarrow \quad n_5 = 37.7 \text{ rpm}$$

Substituting these values into equation (8) gives

$$hp_{\max_1} = \frac{0.1 \times 17}{92} = 0.020$$

$$hp_{\max_5} = \frac{0.5 \times 37.7}{92} = 0.200$$

Therefore, a 1/2 hp motor will be sufficient to provide the power requirements and its output should be reduced to vary between 10 and 50 rpm to provide the accelerations necessary.

Table Assembly	E-001452
Bearing Block	C-001437
Bearing Cover	C-001438
Arm Bearing Block	C-001439
Shaft Extension	B-001440
Block	C-001441
Block Cover	C-001442
Drive Wheel	C-001443
Pin	B-001444
Clevis	B-001445
Beam Support	C-001446
Drive Shaft	B-001447
Center Rod	B-001448
Table	D-001450
Prototype Frame	C-001451

FIGURE 25. LIST OF DRAWINGS,
MOTION TABLE